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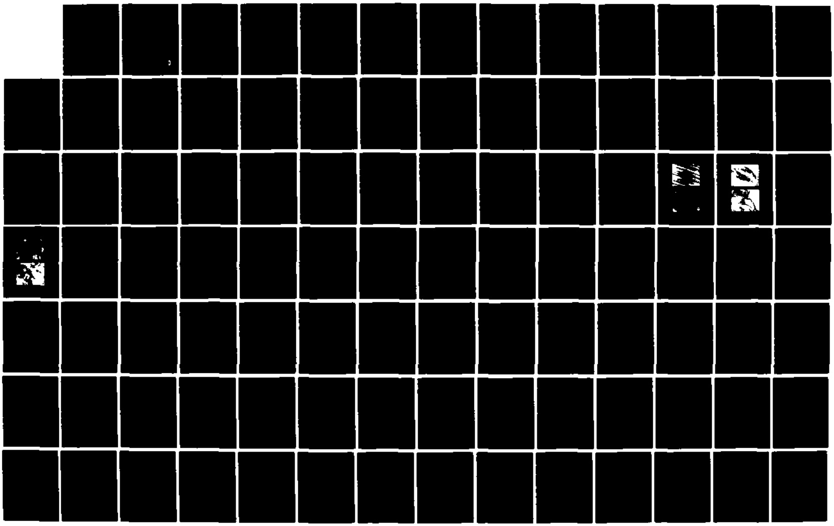

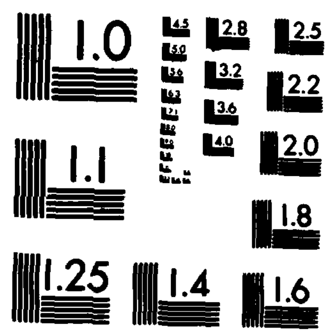

'OPY RESOLUTION TEST CHART

NAPC-PE-94-C

AD-A146 544

EFFECT OF ASPERITY INTERACTIONS ON SCUFFING

JOHN I. Mc COOL

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MAY 1984

FINAL REPORT

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

PREPARED FOR:

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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In this investigation a series of tests were run in a geared roller test machine using three combinations of rolling

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1.0 INTRODUCTION AND SUMMARY

Scuffing

Scuffing, smearing, and scoring are synonyms for a failure mode that affects both gears and rolling contact bearings. It is characterized by an abrupt increase in friction and rapid metal transfer. Once begun it will, if not arrested by a load reduction or decrease in sliding velocity, rapidly become self aggravating due to interfacial metal plowing. It is usually therefore considered a catastrophic failure mode.

It is generally believed that scuffing either will or will not occur depending for a given set of conditions on the magnitude of the load. Interest has, therefore, focused on determining the 'scuffing' load as a function of the many variables that characterize a rolling/sliding contact.

The most widely used criterion for linking scuffing load and the contact variables is one based on the conjunction temperature, i.e. the sum of the bulk temperature of the contacting bodies and the 'flash temperature' i.e. the temperature elevation due to friction in the contact zone. With the flash temperature computed via a thermal analysis, the conjunction temperature criterion links scuffing load to the thermal conductivity, specific heat and density of the contacting bodies, the friction coefficient, the load and the surface velocities of the contacting bodies. It does not specifically link scuffing load to microgeometry though widespread experience suggests that microgeometry exerts an influence.

The objective of the investigation reported herein was to determine whether the characteristics of surface asperity interaction can be used to refine predictions of the load at which lubricated surfaces undergoing relative rolling and sliding, will scuff or smear.

In this investigation a series of tests were run in a geared roller test machine using three combinations of rolling and sliding velocities, and for each velocity condition, a set of polished and ground rollers. A description of the test method is given in Appendix VIII. For the surfaces and speeds used, the film parameter i.e. the ratio of the film thickness h to the mean square roughness σ, ranged from 0.082 to 1.01. The load was increased until the occurrence of scuffing. Each test was then repeated until the load reached half the scuffing load. > p.3

For the same set of velocity conditions the polished specimen pair invariably scuffed at a higher load than the ground pair.

The surfaces were traced using a stylus profile instrument and the output signal digitized and processed to yield mean square values of the profile height, slope and curvature. The computerized system for acquiring and processing such data is described herein along with the associated calibration and system checkout procedure.

The measured surface characteristics were used as input to a simulation model, ASPERSIM, which computes the expected number of micro-contacts and the expected force and area of each.

Significance tests showed that the polished specimens had lower average asperity force and average asperity area than the ground specimens and that these values were correspondingly lower for the unscuffed than for the scuffed tests.

For the specimens that were run to scuffing, (both ground and polished) average asperity area increased with scuffing load. For the polished specimens average force also increased with scuffing load. This is believed to reflect the alteration of microgeometry with load and not a causal relationship between these variables and scuffing load.

Corresponding significance tests for conjunction temperature failed to distinguish a difference due to finish type. Tests using the film parameter i.e. the ratio of film thickness to surface roughness showed a weakly significant effect of finish and scuffing status.

An evaluation using unrun microgeometry showed the polished specimens to have a lower average asperity force than the ground specimens and a lower total expected contact density. It is suggested that the product of average force and expected contact density may be a useful inverse measure of proneness to scuff.

2.0 THEORETICAL BACKGROUND

The following discussion outlines the relevant background that formed the basis for undertaking the investigation reported herein. The scope of the investigation itself is outlined in Section 3.0.

2.1 Constant Conjunction Temperature Criterion

Blok [1] postulated that scuffing occurs when the maximum conjunction temperature reaches a critical value that depends on the specific combination of material and lubricant. Blok expresses the maximum conjunction temperature, T_c, as the sum of the bulk temperature T_b and the maximum 'flash' temperature T_f

$$T_c = T_b + T_f$$

For line contacts the maximum flash temperature is expressed under certain assumptions as follows:

$$T_f = 1.11 \ f \ W \left| V_1^{1/2} - V_2^{1/2} \right| / bw^{1/2}$$

where

w = width of contact

b = $(k \rho c)^{1/2}$ a thermal factor evaluated for the material of the contacting bodies

k = thermal conductivity

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c = specific heat per unit mass

ρ = density

V_1, V_2 = velocities of bodies 1 and 2

W = load/unit length (For elliptical contacts of length 2a and subject to load P, the equivalent load per unit length is taken as $3\ P/4a$).

f = friction coefficient

The assumptions involved in deriving this expression for the flash temperature include:

1) The interfacial temperature is the same for both bodies.

2) Heat is transferred by conduction perpendicular to the contact.

3) The heat flux is semi-elliptically distributed across the contact.

There is no unanimity as to the physical mechanism by which smearing occurs. Explanations that have been proposed fall into these classifications:

1) Loss of the protective capacity of the oil due to an adverse change in the oil as a material. For example, the oil might lose its capacity for removing heat or for inhibiting welding.

2) Loss of the protective capacity of the oil as a structural element. Blok's thermal collapse model is a case in point. [Blok [2]].

3) Loss of the protective capacity of the boundary and oxide layers on the rubbing surfaces. The thermoelastic instability mechanism discussed by Dow and Burton [3] could cause the destruction of boundary layers. Desorption of the boundary layers is discussed by Begelinger and DeGee [4].

2.2 Effect of Surface Roughness

The surface roughness does not appear explicitly in calculating the conjunction temperature.[1] In recent work, however, Durkee and Cheng [6] present data showing differences in scuffing load of a factor of 15 between rough and smooth roller/ring pairs in simple sliding experiments conducted with 52100 material parts and lubricated with an additive-free napthenic oil.

To accommodate the effect of roughness in scuffing prediction is it necessary to use the somewhat artificial device of letting

[1]Winer [5] has, however, proposed a flash temperature correction factor of $[1-0.7\sigma]^{-1}$ (σ = CLA roughness in μm).

the critical conjunction temperature depend on surface finish as well as the specific material and lubricant combination.

The problem with this approach, however, is that testing must be conducted using a range of surface finishes and finishing processes. What is preferable is to develop a means of directly accounting for the effect of surface finish in predicting scuffing load.

The effect of surface roughness on scuffing load must be due to the ways in which the existence of the roughness causes the interfacial conditions to depart from that assumed in Blok's analysis. The most obvious feature of rough contact is that the load is supported by a large number of asperities rather than uniformly over the contact.

Each asperity contact within the conjunction will support a different load depending on the asperity height and local geometry. The elastically deformed asperity contact area will likewise vary randomly from asperity-to-asperity.

The smearing load is thus likely to be influenced by these functional effects of surface roughness:

1) The expected number of asperity contacts within the conjunction

2) the expected asperity contact area and

3) The expected asperity load.

These quantities depend on the statistical microgeometry of the surfaces and i) the applied load for dry contact and ii) the film thickness for EHD contact.

2.3 Calculating Asperity Interaction Behavior

Calculating the expected number of asperities and their contact area and load for a general anisotropic rough surface is possible via the simulation computer program "ASPERSIM" developed at SKF under the sponsorship of the Department of Energy [7]. The input to the program comprises nine quantities known as bispectral moments which describe the height distribution of a surface as well as its frequency and anisotropic character. These nine quantities may be deduced [8] by multiple regression analysis from the mean square of the surface slope and the surface second derivative, calculated from a number of non-parallel profile traces. A detailed description is given in Appendix I.

Signal processing involves digitization of the output of a profile measurement device followed by filtering, editing, and mean square computation. Appropriate software for this digital signal processing has also been developed at SKF and is discussed in Section 4.0.

3.0 PROGRAM SCOPE

The scope of the program reported herein is shown diagrammatically in Figure 1. Scuffing tests were conducted at the Naval Air Propulsion Center (NAPC) using a geared roller test machine. In these tests annular specimens having an outer diameter of 3.01" and a 14" lateral crown radius are run against each other in lubricated contact at independently set rotational speeds. The radially applied load is increased by 50 lbs every 5 minutes until scuffing occurs. The occurrence of scuffing is indicated by a rapid increase in surface temperature and torque. Response variables, in addition to the load at which scuffing occurs, are the friction coefficient and the bulk temperature of the specimens. In the present test program the discs were made of AISI 4720 steel. The test lubricant was a basestock pentaerythritol ester commonly used in formulating MIL-L-23699 lubricants. Half of the specimens had a ground finish on the order of 25μ in. RMS and half had been given an additional polishing operation resulting in a finish on the order of 10μ in. RMS. Three rolling/sliding speed combinations were selected to be run for each surface finish type. The test plan called for running a pair of rings until scuffing occurred at some load P and then to run an identical second pair until a load of half this value (P/2) was reached. The total number of discs is thus

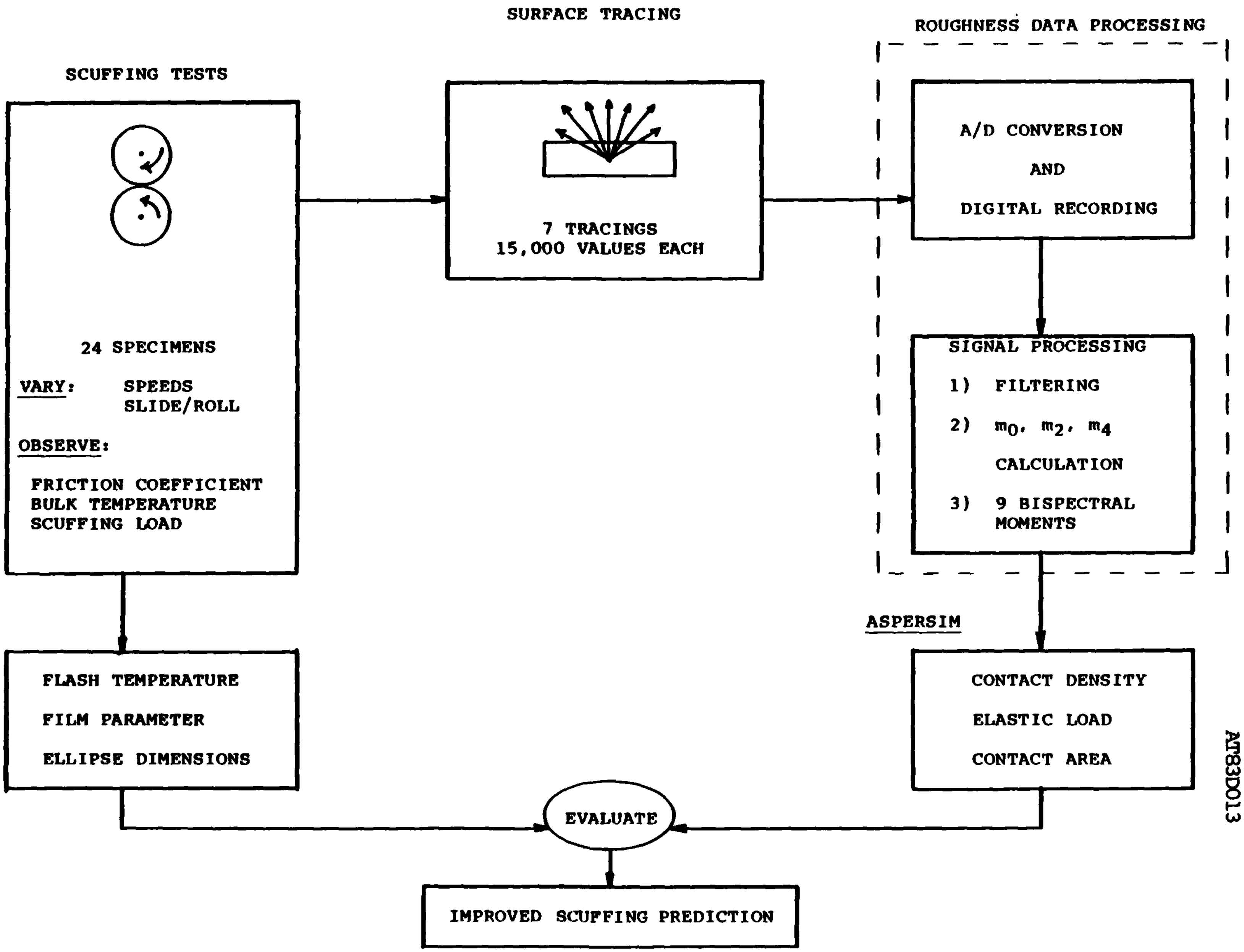

FIGURE 1: SCOPE OF SCUFFING INVESTIGATION

24 corresponding to 3 speed combinations x 2 surface finishes x 2 loads x 2 discs per test.

For each test specimen, 7 surface tracings were initially made using the stylus system described in Section 4.0. The traces were made in the run-in area but not within the scuffed zone and at angular spacings of 22.5° but omitting the circumferential direction.

The analog signal output of each stylus trace was amplified, sampled, digitized and recorded on floppy discs.

Following data acquisition the files of digitized data were read and processed to yield the values of the spectral moments m_0, m_2, m_4 with and without digital filtering between a prescribed set of filter limits.

Using the measured spectral moment values on each of 7 traces, a multiple regression analysis program was used to deduce the 9 bispectral moments which characterize a general anisotropic surface (See Appendix I).

These 9 bispectral moments were to be input to computer program ASPERSIM, for computing the contact density, elastically supported load, and the true area of contact under the assumptions that surface asperities are described as second order functions and that the separation of the surfaces is equal to the calculated elastohydrodynamic lubricant film separating the surfaces at the velocity and temperature of each test. Because of irregularities in some of the initially processed data indicative of extraneous noise, data acquisition was repeated using a single axial trace and the equivalent values of the 9 spectral moments were deduced under the assumption of isotropic bodies. These values were used as ASPERSIM input.

The ASPERSIM output, together with the conventionally computed flash temperature, calculated film parameter, and ellipse dimensions were then examined and evaluated for evidence of an effect of surface roughness on scuffing.

4.0 SURFACE DATA PROCESSING

4.1 Data Acquisition System

Figure 2 is a schematic representation of the data acquisition system used in this investigation. At the heart of the system is the Talysurf 4 surface profile measurement system. In operation, the Talysurf 4 causes a contacting stylus to move across the surface of interest and a voltage proportional to the stylus' excursions is produced. In the conventional mode of operation this voltage is filtered and used in a computation of the CLA average value of the roughness. In the present application the unfiltered voltage is fed into an amplifier and then into the A/D converter that operates in conjunction with a Digital Equipment Corporation PDP 11/03. In order to minimize electrical noise problems, the lowest possible stylus traverse velocity of 0.000466 in/sec is used to assure that the roughness signals correspond to frequencies well below 60 Hz.

4.2 Data Acquisition Software and Calibration

The data is acquired and stored on a floppy disc under the control of the computer program entitled "GETAD".

A system typewriter controls the input/output operations (I/O). Prior to the acquisition of data a calibration constant

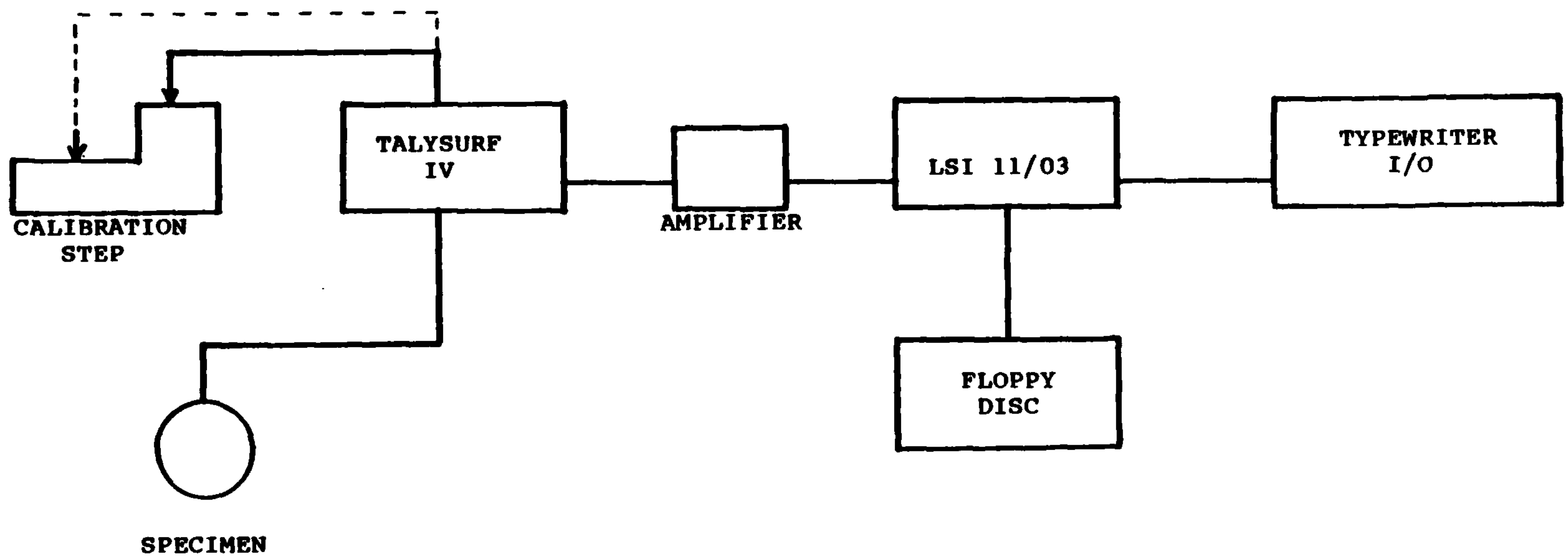

FIGURE 2: ROUGHNESS DATA ACQUISITION SYSTEM

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is computed that relates, for the magnification setting at which the Talysurf is being used, the number of digitized integer values of the signal to the surface displacement. In performing the calibration constant calculation, the user is directed under the control of the program GETAD to place the stylus in contact with the lower level of a calibration step. In this program two Johansson blocks having a height difference of 300 μin. was used for data taken with a Talysurf IV vertical magnification setting of 5000X. The stylus remains in steady contact with the lower of the pair of blocks until 200 digitized values are read. The user is then directed to place the stylus in contact with the higher level of the pair of blocks and an additional 200 digitized values are read. The program then averages the digitized values corresponding to the lower and higher levels of the step and asks the user to supply the actual height difference of the pair of blocks. The step height is then divided by the difference between the average digitized height values to yield the number of linear units (microinches) corresponding to a unit change in the digitized value of the surface. This ratio is termed the calibration factor.

The calibration factor and a user specified 6 digit file name are stored in a "header" block preceding the digitized profile data. The user of the system specifies the total number of points to be digitized and the frequency with which the points are to be taken. These two values together determine the total length of trace.

4.3 Processing Software

The digitized profile data is re-read from the disc and processed by means of another program called "PRODOE". PRODOE reads the header information including the calibration factor and calculates the grand average of the digitized values. It then computes the distance, in digitized units, of each data point from the grand mean and scales it, by means of the calibration factor, into length equivalent units. The mean square surface height (m_0), the mean square slope (m_2) and the mean squared value of the second derivative of the surface (m_4) are computed. m_4 is, to a good approximation, the mean square curvature of the surface.

PRODOE performs an editing function to remove outliers in the data record. For this purpose it uses either a user specified criterion or a computed criterion, being a multiple of the RMS value of the unfiltered surface to determine whether the difference between successive pairs of values could be real. If the criterion is exceeded, the second value is equated to the first. The system reports the number of such replacements that took place.

The user specifies a frequency band f_1 and f_2 in units of cycles per linear distance and the data are then digitally filtered using a cascaded Butterworth filtering scheme described in [9]. PRODOE then computes the values of m_0 and m_2 and m_4 using the filtered signal. It also compiles a histogram of the surface height distribution using a sub-sample of 300 points.

4.4 Validation of Acquisition and Processing Systems

Figures 3-5 show the printed record of the use of program GETAD followed by PRODOE to 1) digitize and record a sine wave of nominal five cycles per second frequency produced by a signal generator and 2) process it through program PRODOE. User input and responses are shown underlined. The dialogue is self explanatory. A total of 5,000 points were sampled and the sampling frequency used was 40 points per second or 8 points per cycle. By entering the stylus traverse velocity of 0.000466" per second, the 5 Hz sine wave became the conceptual equivalent of a sinusoidal surface having a spatial frequency of

$$f = 5 \text{ cycles/sec}/.000466 \text{ in/sec} = 10729 \text{ cycles/inch}$$

The calibration factor was input from the keyboard as unity so that values subsequently displayed are the 'as digitized' numerical values. The output under the heading unfiltered,

```
.R GETAD
  ENTER NAME OF ANALOG SOURCE
       (UP TO 20 CHARACTERS)     SIGGEN

  WILL ALL RUNS COLLECT EQUAL NUMBERS OF DATA POINTS?(Y OR N)   Y
  WILL ALL RUNS COLLECT DATA AT THE SAME FREQUENCY?(Y OR N)     Y

     HOW MANY DATA POINTS? (<=60160)
         USE DECIMAL POINT IF ENTRY > 32767   5000
     WHAT FREQUENCY (HZ<=1.E6)?
         USE DECIMAL POINT IF ENTRY > 32767   40

WHAT IS THE STYLUS TRAVERSE VELOCITY (IN/SEC)?   .000466

CURRENT CALIBRATION FACTOR =  0.0000E+00 MEASURED UNITS / DIGITIZED UNIT
IS THIS SATISFACTORY? (Y OR N)   N

WILL FACTOR BE ENTERED FROM KEYBOARD (K)
OR CALCULATED WITH AID OF A/D BOARD (C)?    K

ENTER CALIBRATION FACTOR AS MEASURED UNITS/DIGITIZED UNIT =
               USE DECIMAL POINT IF VALUE LARGER THAN 32767   1

ENTER FILE NAME (UP TO 6 CHARACTERS)  SI5000
```

FIGURE 3: SINE WAVE PROCESSING RECORD

```
START SIGGEN-THEN PRESS RETURN
  THIS WILL START DATA COLLECTION

  STOP SIGGEN

ANOTHER RUN? (Y OR N)   N

STOP --

.R PRODOE

ENTER FILE NAME (UP TO 6 CHARACTERS)  SI5000

CALCULATING AVERAGE OF ALL POINTS ################### ( 19 PASSES )

CALCULATIONS FOR UNFILTERED-UNSMOOTHED DATA ################### ( 19 PASSES )


                   UNFILTERED, UNSMOOTHED DATA

                            AVE =  2.75127E+02 U-INCH

                            MO =  8.33254E+05 U-INCH**2

                            M2 =  4.24161E+03

                            M4 =  2.16341E+01

CURRENT VALUE OF RES IS  0.38728E+04 IS THIS SATISFACTORY? (Y OR N) Y

CALCULATIONS FOR SMOOTHING DATA ################### ( 19 PASSES )


CURRENT FREQUENCY CUTOFF VALUES ARE :

LOWER CUTOFF =  0.330000D+02
UPPER CUTOFF =  0.320000D+05

ARE THESE SATISFACTORY? (Y OR N)  Y

CALCULATIONS FOR FILTERED-SMOOTHED DATA ################### ( 19 PASSES )


                            DOE DIGITIZED SURFACE DATA

                                       TOTAL NO. OF SURFACE ELEMENTS =     5000.

                                     F1 - LOWER FREQ. BAND CUTOFF =  3.30000E+01 CYCLES/INCH

                                     F2 - UPPER FREQ. BAND CUTOFF =  3.20000E+04 CYCLES/INCH

                                     DX - SURFACE INCREMENT =  1.16500E-05 INCHES

                                 CALIB - CALIBRATION FACTOR = 1.00000E+00 U-INCH/COUNT
```

FIGURE 4: SINE WAVE PROCESSING RECORD (CONTINUED)

M0 = 8.33043E+05 U-INCH**2

M2 = 4.23894E+03

M4 = 2.16090E+01

IFLAG = 0

HISTOGRAM OF FILE DK SI5000OFF

MAX = 0.13177E+04 MIN = -0.13641E+04

TOTAL NUMBER OF POINTS = 294.

UPPER CELL BOUNDARY	NORMALIZED CUMULATIVE FREQUENCY	POINT FREQUENCY	
-0.11964E+04	0.1293	38	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.10288E+04	0.2143	25	XXXXXXXXXXXXXXXXXXXXXXXXX
-0.86122E+03	0.2721	17	XXXXXXXXXXXXXXXXX
-0.69361E+03	0.3197	14	XXXXXXXXXXXXXX
-0.52600E+03	0.3605	12	XXXXXXXXXXXX
-0.35839E+03	0.4014	12	XXXXXXXXXXXX
-0.19078E+03	0.4524	15	XXXXXXXXXXXXXXX
-0.23171E+02	0.4932	12	XXXXXXXXXXXX
0.14444E+03	0.5340	12	XXXXXXXXXXXX
0.31205E+03	0.5816	14	XXXXXXXXXXXXXX
0.47966E+03	0.6156	10	XXXXXXXXXX
0.64727E+03	0.6735	17	XXXXXXXXXXXXXXXXX
0.81488E+03	0.7211	14	XXXXXXXXXXXXXX
0.98249E+03	0.7823	18	XXXXXXXXXXXXXXXXXX
0.11501E+04	0.8605	23	XXXXXXXXXXXXXXXXXXXXXXX
0.13177E+04	1.0000	41	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

ANOTHER RUN? (Y OR N)

FIGURE 5: SINE WAVE PROCESSING RECORD (CONTINUED)

unsmoothed data shows the average expressed in length units. It is positive indicating some small positive bias in the signal generator output. The quantity RES is used for editing or smoothing wild points. We have selected it to be 3 standard deviations of the difference $x_1 - x_2$ of two independent random values. Since $\sigma^2 x_1 - x_2 = \sigma^2 x_1 + \sigma^2 x_2$, $3\sigma_{x_1 - x_2}$ becomes, if x_1 and x_2 have the same variance $= 3 \bullet \sqrt{2} \bullet \sigma_x = 4.24\sigma_x = 4.24\ m_0^{1/2}$. The default frequency band pass is f_1=33 cycles/in. to f_2 = 32,000 cycles/in. Since the spatial equivalent of the sine wave used here was 10,729 cycles/in., it fell well within this pass band and the m_0, m_2, and m_4 values after filtering differ little from the unfiltered values. The variable IFLAG denotes the number of points that were edited using the RES criterion. The histogram shows the typical "U" shape characteristic of sinusoids.

To determine the plausibility of the computed spectral moments they were compared to the theoretical values for a sine wave. A sine wave of amplitude A and spatial frequency f has the following theoretical values of m_0, m_2 and m_4:

$$m_0 = A^2/2$$

$$m_2 = (2\pi f A)^2/2$$

$$m_4 = (2\pi f)^4 A^2/2$$

From the maximum and minimum values printed just above the histogram the amplitude is deduced to be A = 1341 giving

$$m_0 = (1341)^2/2 = 8.99E5 \text{ vs. } 8.33E5 \ (\mu in)^2$$

For the nominal frequency of 5 cycles/sec = 10729 cycles/in.

$$m_2 = (2\pi \bullet 10729E6 \bullet 1341)^2/2 = 4.09E3 \text{ vs. } 4.24E3$$

and
$$m_4 = \frac{(2\pi \bullet 10729E\text{-}6)^4 \ (1341)^2}{2} = 18.5 \text{ vs. } 21.6 \ (\mu in)^{-2}$$

It is seen that the computed quantities are all of the correct order of magnitude, but differ from the theoretical values by up to 14% (m_4). The actual error is not believed to be this great. The amplitude used in the above calculations was determined from just two data values and is subject to error due to noise. The frequency was also only nominal. As a further check we determined the A and f values implicit in the measured m_0 and m_2 and used them to predict m_4. The results are

$$m_0 = A^2/2 = 8.33254E5$$

$$A = 1290 \ \mu in.$$

$$m_2 = (2\pi f \bullet 1290E\text{-}6)^2/2 = 4.24161E3$$

$$f = 11363$$

so that m_4 becomes,

$$m_4 = \frac{(2\pi \bullet 11363E\text{-}6)^4 (1341)^2}{2} = 23.4$$

which is an 8% error.

5.0 TRACING PARAMETERS

In processing roughness data it is necessary to specify the sampling interval Δx and the total length of trace L or, alternatively, the sampling frequency f_s (samples/sec) and the total number of sampled values N. These quantities are related as follows:

$$L = N\Delta x$$

$$N = f_s/V \bullet L$$

so that, $\Delta x = V/f_s$

where V is the stylus traverse velocity. In the initial tracing work in this program a spacing of 14.5 μin was selected. This value is comparable to that used in other profile digitization studies in the literature (cf. Sidik and Coy [10]). A total of N = 15000 points was selected giving a total record length of

$$L = 15000 \bullet 14.5E\text{-}6 = 0.22 \text{ in.}$$

The sampling frequency was

$$f_s = V/\Delta x = 0.000466 \text{ in/sec}/14.5E\text{-}6 = 32.2 \text{ samples/sec}$$

In processing the data the initial band pass chosen for digital filtering was f_1 = 33 cycles/in. and f_2 = 10,000 cyles/in.

The lower frequency corresponds to the usual filter setting for precision specimens recommended by the Talysurf supplier. The upper limit is believed to be well below the frequency at which electrical noise exceeds the signal level (cf. Church [11]). The upper limit was further refined in subsequent processing as discussed in Section 7.0.

6.0 SCUFFING TEST RESULTS

Table 1 summarizes the results of the scuffing tests conducted at NAPC. The tests numbered 1A through 6A, shown in Column 1, were the tests which proceeded to scuffing as indicated in Column 3. Tests 1B to 6B were conducted at the corresponding conditions to Tests 1A through 6A but proceeded only until a load equal to one-half the associated scuffing load was obtained. It is seen that consecutive pairs of tests in each series (scuffed and unscuffed) were conducted at identical rolling and sliding speeds but on two surface finish types, namely, ground and polished. Sliding and rolling velocity are indicated in Columns 4 and 5 and the linear speeds of the faster and slower discs in each test are given in Columns 6 and 7. The load at scuffing, or in the case of Tests 1B to 6B, the load at test termination is given in Column 8. In calculating film thickness the oil viscosity should ideally be evaluated at the temperature of the thin layer of oil in the contact inlet. However, this temperature and hence the film thickness varies throughout the duration of the test. At startup, when the discs are cold, the oil inlet temperature is well aproximated by the oil supply temperature (180°F). At the highest load attained in the test, the relevant temperature is somewhere between the bulk temperature and the conjunction temperature.

TEST NO.	FINISH TYPE	SCUFFED ?	SLIDING VELOCITY V_S(in/sec)	ROLLING VELOCITY V_R(in/sec)	V_1 (in/sec)	V_2 (in/sec)	LOAD P (lbs)	FILM THICKNESS h (μ in) T=180°F	T=T_c	FRICTION COEFFICIENT f	FLASH TEMPERATURE T_f-°F	BULK TEMPERATURE T_B-°F	CONJUNCTION TEMPERATURE T_B-°F
1A	G	Y	138	345	414	276	966	13.4	3.95	0.047	177	280	457
2A	P	Y	138	345	414	276	1166	13.2	4.27	0.036	149	276	425
3A	G	Y	60	305	336	276	3516	11.3	3.76	0.034	112	303	415
4A	P	Y	60	305	336	276	3716	11.3	3.65	0.034	115	310	425
5A	G	Y	121	610	673	552	1466	19.1	7.38	0.025	76	291	367
6A	P	Y	121	610	673	552	2116	19.1	5.24	0.025	91	400	491
1B	G	N	138	345	414	276	483	14.0	5.88	0.041	109	232	341
2B	P	N	138	345	414	276	583	13.8	6.47	0.031	91	221	312
3B	G	N	60	305	336	276	1758	11.8	4.25	0.047	110	282	392
4B	P	N	60	305	336	276	1858	11.8	4.86	0.039	94	256	350
5B	G	N	121	610	673	552	733	20.0	9.99	0.025	54	252	306
6B	P	N	121	610	673	552	1058	20.0	8.89	0.022	57	269	326

TABLE 1: SCUFFING TEST RESULTS

Column 9 gives the film thickness calculated at the oil supply temperature and at the conjunction temperature using Hamrock and Dowson's formula for fully flooded elliptical EHD contacts. A thermal correction for inlet heating due to Murch and Wilson [15] has been applied and resulted in an approximate 10% reduction from isothermal conditions. Column 10 contains the friction coefficient measured in the tests, and Column 11 the computed flash temperature. Column 12 is the observed bulk temperature and Column 13 the sum of the flash and bulk temperatures. In computing flash temperature it was necessary to compensate for the fact that the contact was elliptical and not rectangular as assumed in Blok's formula. This was done following Kelley [22] by using an equivalent unit load W_e = 3P/4a, where P = scuffing load and a = half width of the elliptical contact.

Reviewing the data in Table 1 it is seen that in general for the Tests 1A through 6A for given rolling and sliding velocities the scuffing load is consistently higher in the polished, as opposed to the ground tests. This is shown in the plotted Figure 6 showing scuffing load against velocity 'condition'. This difference, however, is not, particularly in Tests 3A and 4A, percentually large. Repeated tests at each condition would have been useful to gauge whether the smearing load differences bet-

VELOCITY CONDITION	V_S	V_R
1	138	345
2	60	305
3	121	610

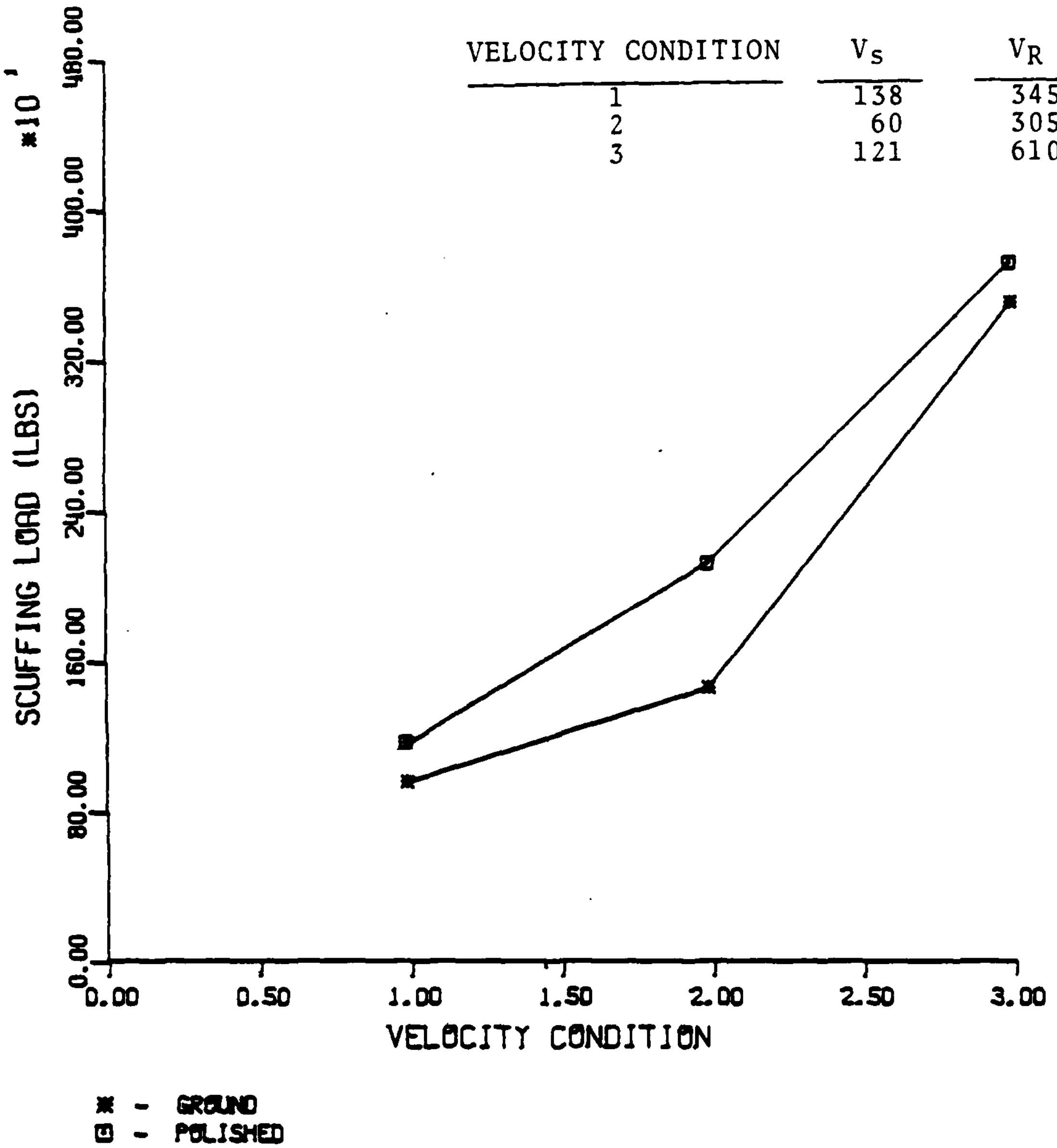


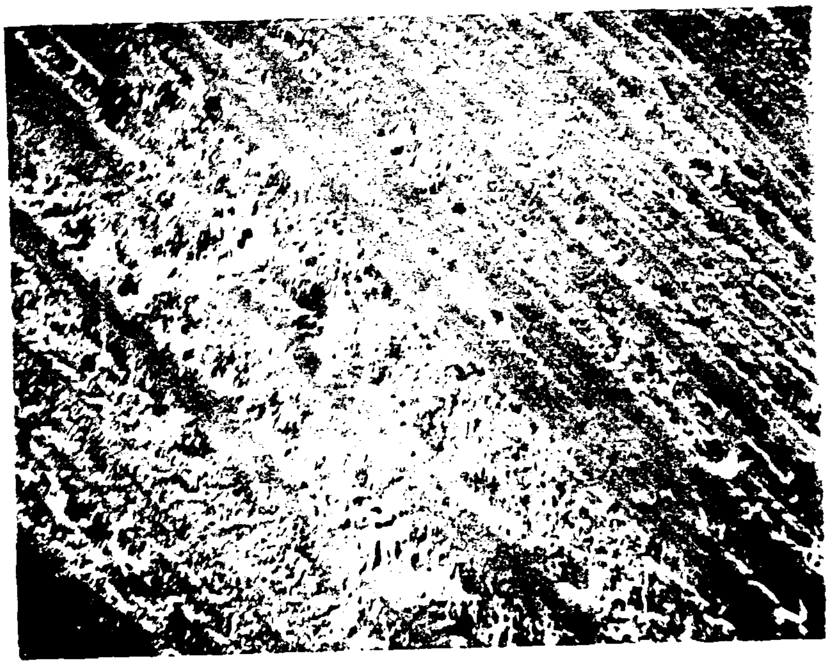
FIGURE 6: SCUFFING LOAD VS. VELOCITY CONDITION

ween polished and ground are real. We have assumed them to be so. Tests 3A and 4A exhibited the highest scuffing load and had the lowest sliding speed. Tests 1A and 2A had the lowest scuffing load and the highest slide to roll ratio. Tests 5A and 6A had the same slide to roll ratio as Tests 3A and 4A but the sliding and rolling magnitudes were double those of Tests 3A and 4A. Since the observed scuffing load in Tests 5A and 6A are substantially lower than the value in Tests 3A and 4A, it is clear that scuffing is affected not just by the ratio of sliding to rolling but by their absolute values. Tests 1A and 2A have a comparable rolling velocity to Tests 3A and 4A but somewhat more than twice the sliding velocity. Here again, the scuffing load in Tests 1A and 2A is substantially below that obtained in Tests 3A and 4A. This indicates the important effect of sliding velocity on scuffing load.

Figure 7 shows comparative SEM photographs of the unrun ground and polished specimens. The surfaces are seen to be characteristically distinct with strong directionality evident in both. The ground surface exhibits very marked furrowing and the polished surface shows traces of where the furrows have been abraded away by the polishing operation.

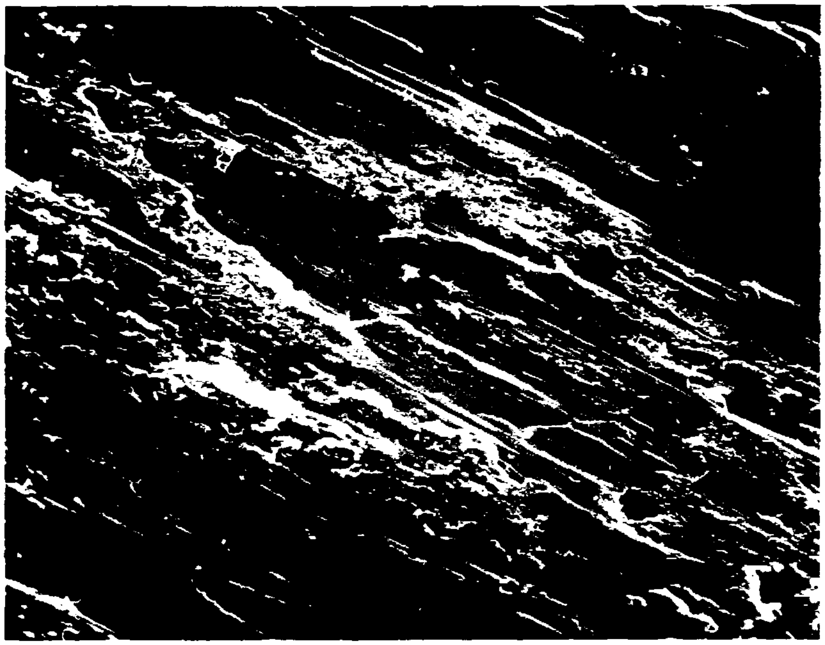
Figure 8 shows SEM photographs at 400X and 1000X within the scuffed area of the faster running of the two discs that ran

GROUND SPECIMEN - 1000X

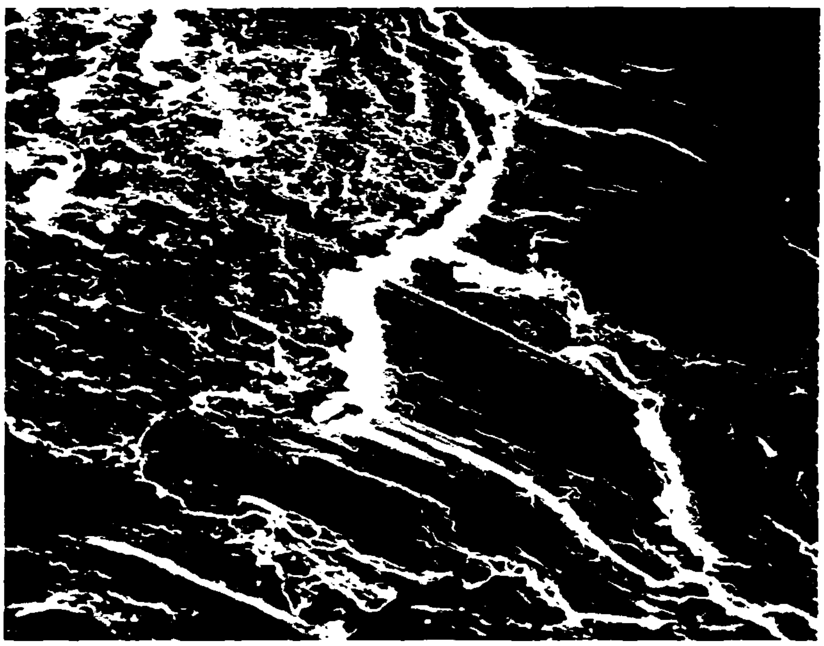


POLISHED SPECIMEN - 1000X

FIGURE 7: SEM PHOTOS OF UNRUN SURFACES



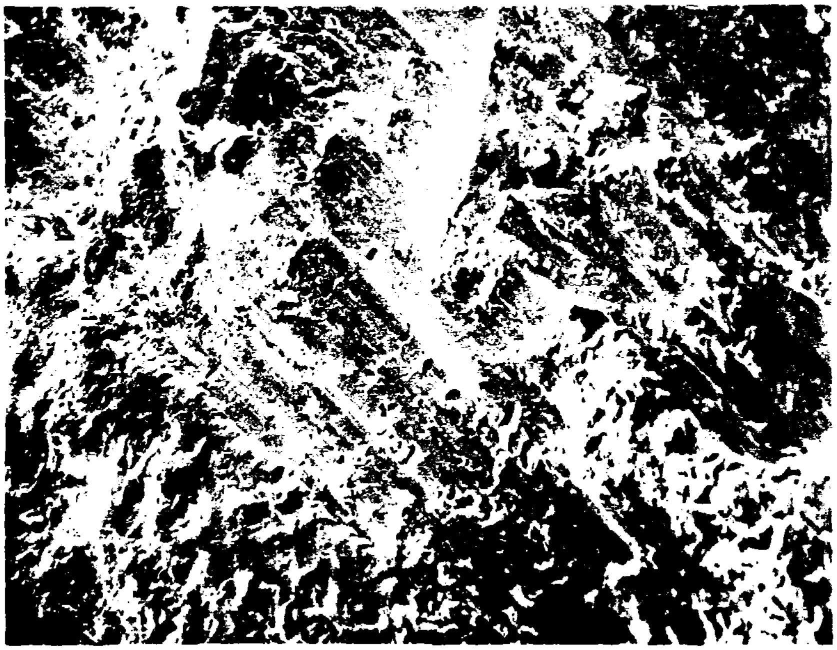
400X



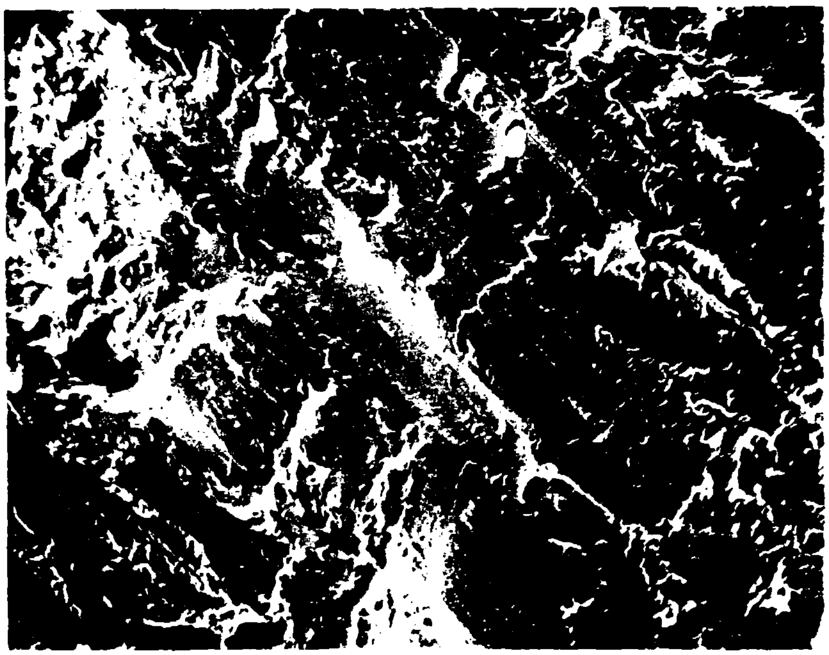
1000X

FIGURE 8: SCUFFED GROUND SURFACE
FAST DISC TEST 1A
SCUFFING LOAD = 966 LBS.

in Test 1A. This test had the lowest observed smearing load and severe damage to the surfaces is quite evident in the photographs. Some visual evidence of directionality still persists despite the severe working of the surface. Figure 9 is a comparable set of photographs taken at 500X and 1000X in the scuffed area of the polished disc that was used as the faster running disc in Test 2A. This test had the second lowest scuffing load, 1166 lbs, observed during the test program. Again, evidence of gross damage is abundant but considerably less dramatic than the severe surface damage seen in the ground surface photographs.



500X



1000X

FIGURE 9: SCUFFED POLISHED SURFACE
FAST DISC TEST 2A
SCUFFING LOAD = 1166 LBS.

7.0 SURFACE TRACING RESULTS

7.1 Specimen Macro-Geometry

Figures 10 and 11 show a succession of 7 traces made on an unrun ground specimen as a preliminary appraisal of specimen macro-geometry. The trace made in a direction of 90° to the marked face of the specimen exhibits an error in form characteristic of the scuffing test specimen. If the contour had had the nominal crown radius the trace would appear as a straight line with fluctuations due to surface roughness alone. The deep valley and hill represent a departure from the ideal crowning radius. A consequence of this departure is that a low magnification level must be used in order to stay within the range of the Talysurf output limits. The result is that the roughness itself spans a relatively narrow range in the output signal. Whenever the roughness is a small percentage of full scale, the magnitude of quantization error is increased. Unfortunately, there is no convenient way in which this can be avoided.

Another unwanted effect of the non-ideal macro-geometry is that the macro-stress distribution across the disks is affected, most likely in a uniquely different way for each specimen pair, adding to overall test variability.

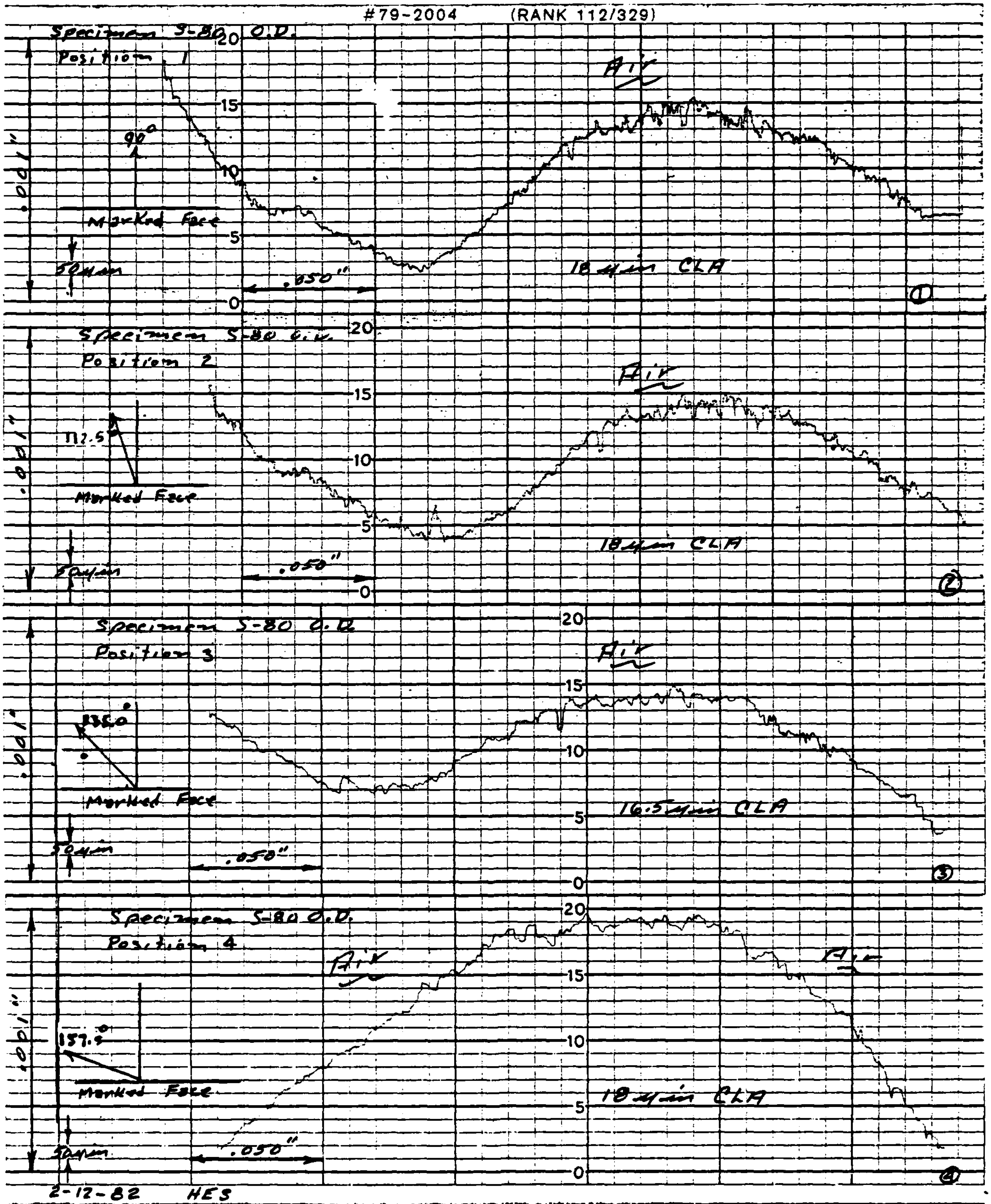


FIGURE 10; SPECIMEN MACRO-GEOMETRY
VARIOUS TRACING ANGLES

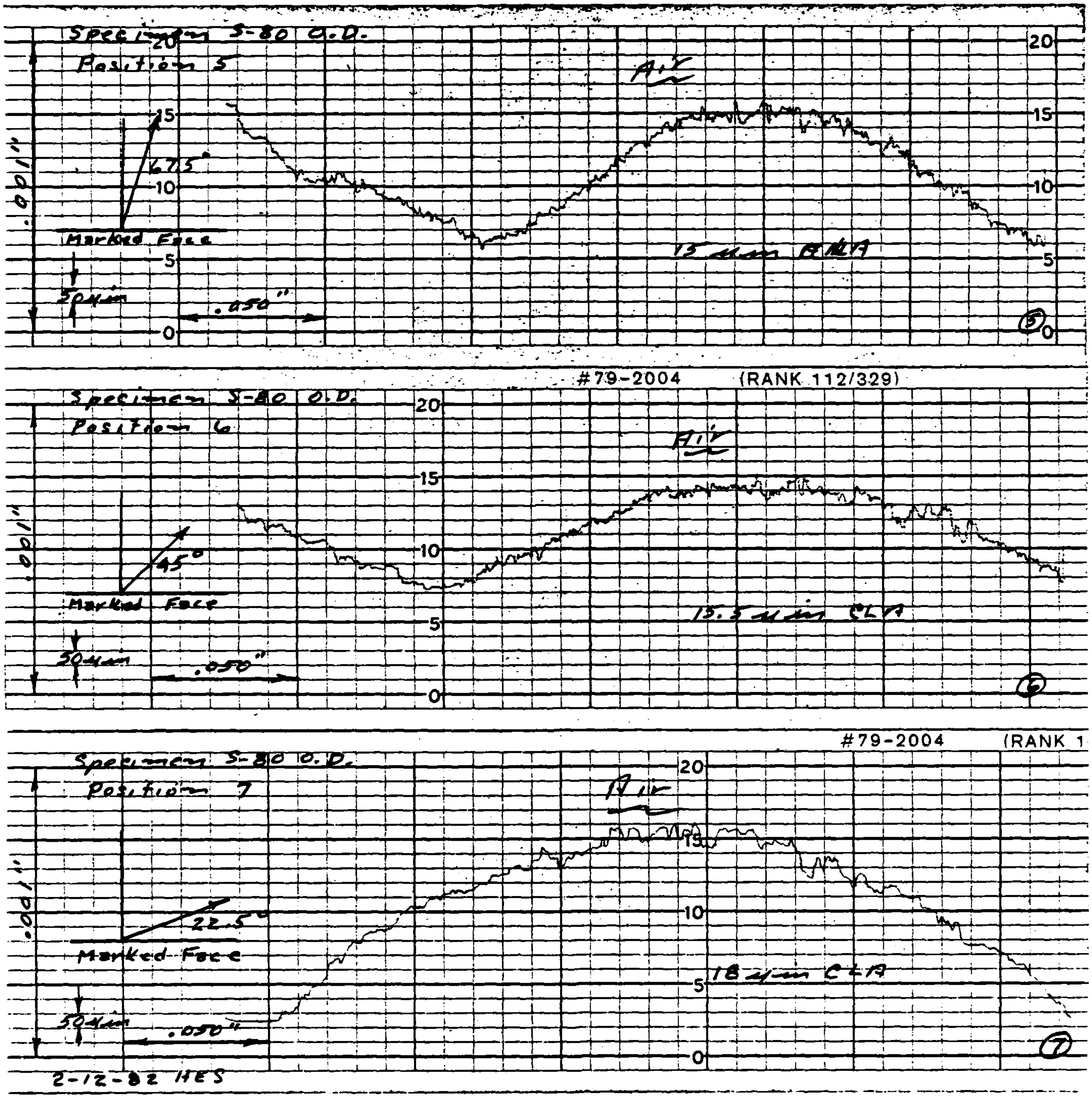


FIGURE 11: SPECIMEN MACRO-GEOMETRY
VARIOUS TRACING ANGLES (CONTINUED)

The two traces made at angles 22½° to the circumferential direction are close enough to being circumferential that the hill and valley macro-geometry is not seen.

The traces discussed above indicated that vertical magnifications of 2,000X or 5,000X would be necessary. Figure 12 shows traces over two calibration steps selected so as to occupy most of the dynamic range of the Talysurf at vertical magnifications of 2,000X and 5,000X. The respective step heights are 900 and 300 micro-inches.

7.2 Acquisition of Digitized Roughness Data

Tables 2 and 3 show the measured values of m_0, m_2, and m_4 obtained from PRODOE for 15 specimens. The first column in these tables is a specimen serial number assigned by NAPC along with a test number as specified in the scuffing test summary in Table 1. The letter F or S is prefixed to the test number to indicate whether this specimen was the fast or slow member of the mating pair. The second column shows the tracing angle with 0° representing the axial direction on the specimen and 90° the circumferential direction. As noted previously, however, the 90° direction was omitted in the measurement work. As noted in Appendix II, the value of m_4 is constrained by reason of the stylus tip radius to be less than 10^{-4} $(\mu \text{ in})^{-2}$. There are several

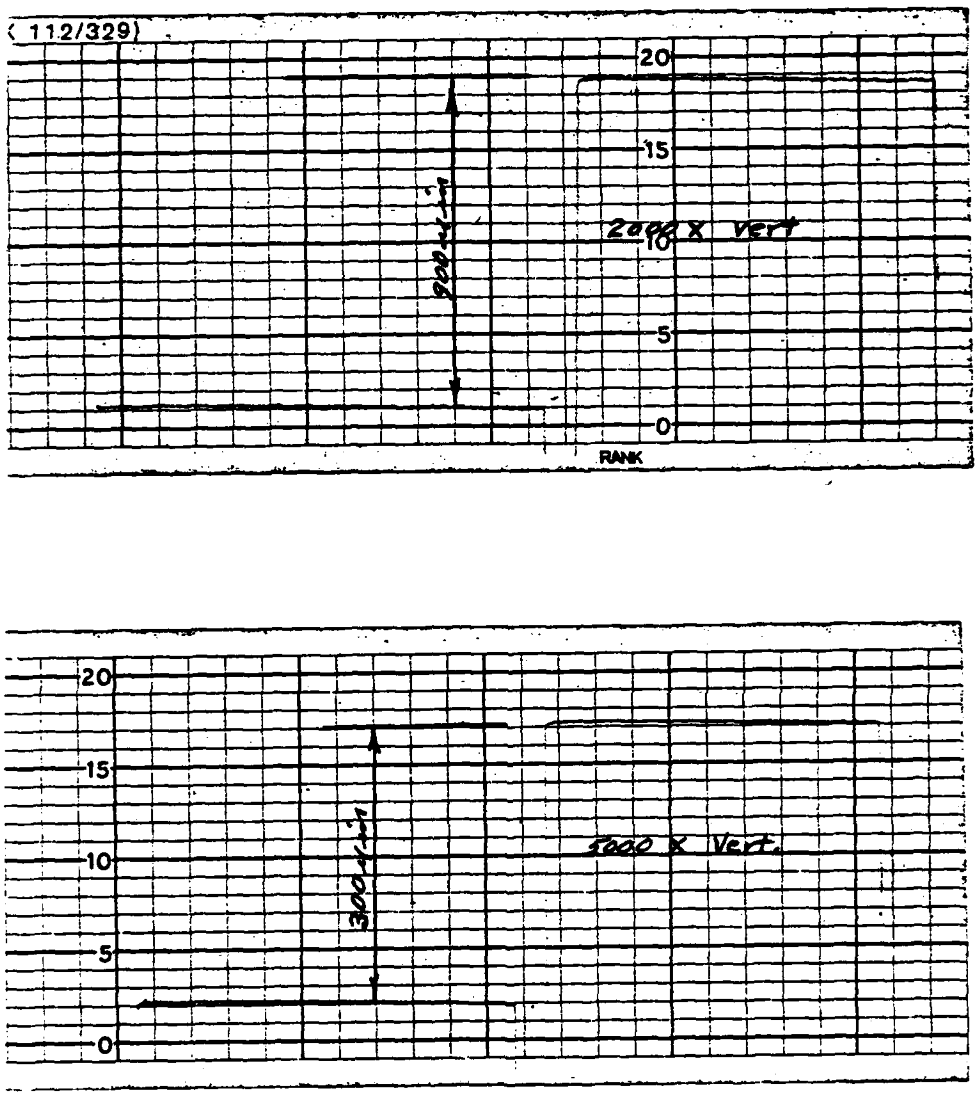


FIGURE 12: CALIBRATION STEPS

SPECIMEN NO./FILE NO.	ANGLE (DEG)	m_0 (μin^2)	m_2	m_4 (μin^{-2})	SPECIMEN NO./FILE NO.	ANGLE (DEG)	m_0 (μin^2)	m_2	m_4 (μin^{-2})
S-63/F1A (GROUND)	0	5.69563×10^{2}	8.91980×10^{-1}	3.01825×10^{-3}	S-85/F4A (POLISHED)	0	7.08460×10^{1}	1.07010×10^{-1}	3.61782×10^{-4}
	22.5	5.78842×10^{2}	8.99846×10^{-1}	2.99887×10^{-3}		22.5	7.27218×10^{1}	1.12950×10^{-1}	3.75255×10^{-4}
	45.0	5.72919×10^{2}	8.98261×10^{-1}	3.04607×10^{-3}		45.0	7.30595×10^{1}	1.14064×10^{-1}	3.80229×10^{-4}
	67.5	5.57345×10^{2}	8.95642×10^{-1}	3.03515×10^{-3}		67.5	7.37921×10^{1}	1.12689×10^{-1}	3.72361×10^{-4}
	112.5	5.68731×10^{2}	8.96990×10^{-1}	3.02391×10^{-3}		112.5	7.47322×10^{1}	1.16864×10^{-1}	3.92476×10^{-4}
	135.0	5.83593×10^{2}	9.14146×10^{-1}	3.01703×10^{-3}		135.0	8.04307×10^{1}	1.19991×10^{-1}	3.96839×10^{-4}
	157.5	5.74799×10^{2}	8.87857×10^{-1}	2.98795×10^{-3}		157.5	7.99206×10^{1}	1.24387×10^{-1}	4.17527×10^{-4}
S-64/S1A (GROUND)	0	5.68485×10^{2}	8.72614×10^{-1}	2.90738×10^{-3}	S-74/S4A (POLISHED)	0	8.68919×10^{1}	1.30094×10^{-1}	4.29721×10^{-4}
	22.5	5.49801×10^{2}	8.63145×10^{-1}	2.92024×10^{-3}		22.5	8.92640×10^{1}	1.36137×10^{-1}	4.53442×10^{-4}
	45.0	5.77393×10^{2}	9.10018×10^{-1}	3.02527×10^{-3}		45.0	8.88809×10^{1}	1.37634×10^{-1}	4.65841×10^{-4}
	67.5	5.82104×10^{2}	9.18199×10^{-1}	3.01544×10^{-3}		67.5	8.79658×10^{1}	1.40362×10^{-1}	4.70870×10^{-4}
	112.5	5.65371×10^{2}	8.64223×10^{-1}	2.92818×10^{-3}		112.5	8.85773×10^{1}	1.38826×10^{-1}	4.64146×10^{-4}
	135.0	6.08779×10^{2}	9.37230×10^{-1}	3.09104×10^{-3}		135.0	9.33314×10^{1}	1.45222×10^{-1}	4.83460×10^{-4}
	157.5	5.73581×10^{2}	8.90843×10^{-1}	3.00566×10^{-3}		157.5	9.23555×10^{1}	1.40095×10^{-1}	4.68893×10^{-4}
S-3/F3A (GROUND)	0	5.06756×10^{2}	7.78858×10^{-1}	2.58811×10^{-3}	S-13/F5A (GROUND)	0	5.61149×10^{2}	8.73582×10^{-1}	2.91865×10^{-3}
	22.5	4.97629×10^{2}	7.75226×10^{-1}	2.55591×10^{-3}		22.5	6.02475×10^{2}	8.83669×10^{-1}	2.33140×10^{-3}
	45.0	5.91970×10^{2}	8.09345×10^{-1}	2.67299×10^{-3}		45.0	5.79291×10^{2}	$8.90960\times1\ ^{-1}$	2.99269×10^{-3}
	67.5	5.38903×10^{2}	8.18245×10^{-1}	2.65929×10^{-3}		67.5	5.86173×10^{2}	9.03269×10^{-1}	2.99825×10^{-3}
	112.5	5.29337×10^{2}	8.21296×10^{-1}	2.73123×10^{-3}		112.5	5.85069×10^{2}	8.97964×10^{-1}	3.00872×10^{-3}
	135.0	5.26889×10^{2}	8.23453×10^{-2}	2.75356×10^{-3}		135.0	5.87251×10^{2}	9.19718×10^{-1}	3.06100×10^{-3}
	157.5	5.95163×10^{2}	9.18788×10^{-1}	3.04950×10^{-3}		157.5	6.05785×10^{2}	9.67899×10^{-1}	3.22697×10^{-3}
S-4/S3A (GROUND)	0	9.21712×10^{1}	1.43670×10^{-1}	4.75338×10^{-4}					
	22.5	9.04377×10^{1}	1.41903×10^{-1}	4.68920×10^{-4}					
	45.0	9.06914×10^{1}	1.38120×10^{-1}	4.57246×10^{-4}					
	67.5	8.89149×10^{1}	1.38077×10^{-1}	4.60706×10^{-4}					
	112.5	9.22148×10^{1}	1.43408×10^{-1}	4.80250×10^{-4}					
	135.0	9.28104×10^{1}	1.39894×10^{-1}	4.63759×10^{-4}					
	157.5	9.20662×10^{1}	1.42657×10^{-1}	4.71375×10^{-4}					

TABLE 2: SURFACE ROUGHNESS DATA - 7 ANGULARLY SPACED PROFILES PER SPECIMEN

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SPECIMEN NO./FILE NO.	ANGLE (DEG)	m_0 (μin^2)	m_2	m_4 (μin^{-2})	SPECIMEN NO./FILE NO.	ANGLE (DEG)	m_0 (μin^2)	m_2	m_4 (μin^{-2})
S-11/F6A (POLISHED)	0	9.41333×10^{1}	1.47655×10^{-1}	4.93298×10^{-4}	S-15/F5B (GROUND)	0	6.17272×10^{2}	3.02643×10^{-2}	4.78554×10^{-5}
	22.5	9.17418×10^{1}	1.43451×10^{-1}	4.89300×10^{-4}		22.5	5.91661×10^{2}	2.61151×10^{-2}	4.30674×10^{-5}
	45.0	9.69677×10^{1}	1.47545×10^{-1}	4.82248×10^{-4}		45.0	4.16787×10^{2}	9.11312×10^{-3}	9.13416×10^{-6}
	67.5	9.52331×10^{1}	1.40441×10^{-1}	4.60518×10^{-4}		67.5	1.15102×10^{3}	2.58011×10^{-2}	4.98841×10^{-5}
	112.5	9.20792×10^{1}	1.42017×10^{-1}	4.78664×10^{-4}		112.5	1.50233×10^{3}	3.53853×10^{-2}	7.30478×10^{-5}
	135.0	9.33076×10^{1}	1.46267×10^{-1}	4.89693×10^{-4}		135.0	3.71844×10^{2}	1.57065×10^{-2}	3.22087×10^{-5}
	157.5	9.18883×10^{1}	1.42571×10^{-1}	4.79344×10^{-4}		157.5	4.34670×10^{2}	3.10046×10^{-2}	6.64262×10^{-5}
S-12/S6A (POLISHED)	0	5.56649×10^{2}	8.67324×10^{-1}	2.87862×10^{-3}	S-16/S5B (GROUND)	0	2.34027×10^{2}	1.73835×10^{-2}	4.65714×10^{-5}
	22.5	5.32763×10^{2}	8.25456×10^{-1}	2.74242×10^{-3}		22.5	3.30695×10^{2}	1.58166×10^{-2}	4.04731×10^{-5}
	45.0	5.53767×10^{2}	8.68822×10^{-1}	2.91568×10^{-3}		45.0	5.44027×10^{2}	1.55046×10^{-2}	3.90079×10^{-5}
	67.5	5.61536×10^{2}	8.62498×10^{-1}	2.88005×10^{-3}		67.5	4.58701×10^{3}	6.36499×10^{-2}	9.38172×10^{-5}
	112.5	5.47514×10^{2}	8.44894×10^{-1}	2.84525×10^{-3}		112.5	2.74058×10^{3}	4.37791×10^{-2}	7.03630×10^{-5}
	135.0	5.48620×10^{2}	8.50930×10^{-1}	2.87200×10^{-3}		135.0	6.47675×10^{2}	2.62259×10^{-2}	5.91834×10^{-5}
	157.5	5.55441×10^{2}	8.51564×10^{-1}	2.85439×10^{-3}		157.5	4.56364×10^{2}	1.66626×10^{-2}	3.67364×10^{-5}
S-9/F4B (POLISHED)	0	3.66328×10^{2}	4.35498×10^{-3}	8.23214×10^{-6}	S-83/F6B (POLISHED)	0	1.03611×10^{2}	1.10226×10^{-2}	1.84349×10^{-5}
	22.5	1.54228×10^{2}	3.54741×10^{-3}	7.28907×10^{-6}		22.5	1.77932×10^{2}	8.69739×10^{-3}	1.40258×10^{-5}
	45.0	7.37750×10^{1}	3.43898×10^{-3}	7.65288×10^{-6}		45.0	1.02237×10^{2}	5.93537×10^{-3}	1.35066×10^{-5}
	67.5	6.67592×10^{2}	9.22683×10^{-3}	1.31735×10^{-5}		67.5	6.07290×10^{2}	1.15710×10^{-2}	1.97382×10^{-5}
	112.5	7.14054×10^{2}	1.09688×10^{-2}	1.52904×10^{-5}		112.5	6.89468×10^{2}	1.18971×10^{-2}	2.32926×10^{-5}
	135.0	7.66339×10^{1}	3.41394×10^{-3}	7.32113×10^{-6}		135.0	1.59673×10^{2}	8.32708×10^{-3}	1.80516×10^{-5}
	157.5	3.59823×10^{2}	4.05602×10^{-3}	7.61359×10^{-6}		157.5	1.21227×10^{2}	1.08477×10^{-2}	2.03973×10^{-5}
S-10/S4B (POLISHED)	0	1.67963×10^{2}	3.51377×10^{-3}	7.22122×10^{-6}	S-8/S6B (POLISHED)	0	6.83183×10^{2}	3.20475×10^{-2}	8.48600×10^{-5}
	22.5	3.69825×10^{2}	3.87424×10^{-3}	6.81558×10^{-6}		* 22.5	—	—	—
	45.0	3.00883×10^{2}	2.73023×10^{-3}	6.0224×10^{-6}		45.0	6.83931×10^{2}	1.78799×10^{-2}	5.76405×10^{-5}
	67.5	5.99646×10^{2}	1.01124×10^{-2}	1.50680×10^{-5}		67.5	2.27382×10^{3}	5.82522×10^{-2}	1.26411×10^{-4}
	112.5	7.88133×10^{2}	9.01035×10^{-3}	1.35005×10^{-5}		112.5	1.26849×10^{3}	3.24091×10^{-2}	7.62121×10^{-5}
	135.0	3.53139×10^{2}	2.97845×10^{-3}	6.08247×10^{-6}		135.0	1.86490×10^{2}	2.17155×10^{-2}	6.53769×10^{-5}
	157.5	1.68731×10^{2}	3.89895×10^{-3}	8.79753×10^{-6}		157.5	1.65369×10^{2}	2.02902×10^{-2}	6.22460×10^{-5}

* DATA FILE ERROR

TABLE 3: SURFACE ROUGHNESS DATA - 7 ANGULARLY SPACED PROFILES PER SPECIMEN (CONTINUED)

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instances in the data of Tables 2 and 3 in which the measured value of m_4 exceeds 10^{-4}. This is taken to be evidence of extraneous, high frequency noise from electronic or vibration sources. A second observation is that the value of m_0 is very consistent, i.e. varies very little, with respect to tracing direction in several of the tests. Inspection reveals that the specimens for which m_0 is consistent coincides with the specimens for which m_4 exceeds 10^{-4}. One explanation could be that the extraneous, high frequency noise which causes m_4 to be too large is providing a high level background which tends to mask any true differences with tracing direction. For specimens which appear consistent, the value of m_0 is in the neighborhood of 500-600 $(\mu\ in)^2$ for the ground specimens and in the neighborhood of 70 to 90 $(\mu\ in)^2$ for the polished specimens. Specimens S3A and S6A, however, are exactly the opposite to this observation raising the question of whether the data for these specimens might have been reversed. Examining the order in which the data were taken, there appeared to be a clear relationship between variability in m_0 with respect to tracing direction, and the order of data acquisition, suggesting a reduction in scatter as the operator acquired skill in the use of the newly developed system.

Because of these various anomalies that were noted in the data it was decided to repeat the entire data acquisition process but confining the measurements to a single trace in the axial direction. It was further decided to:

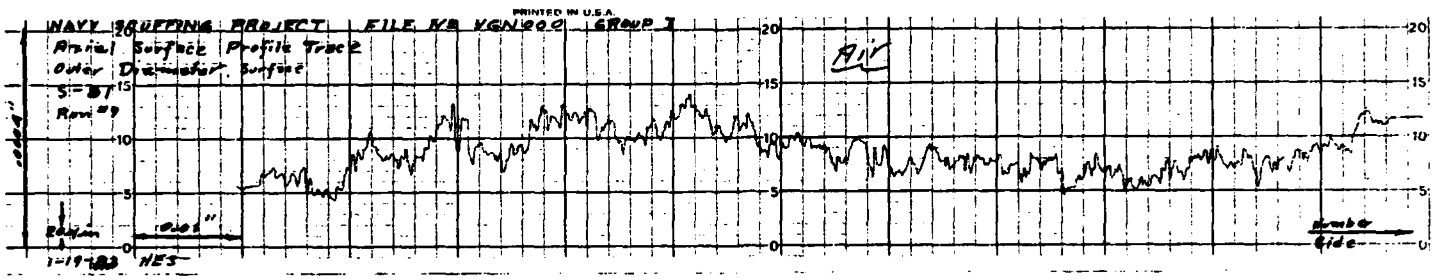
1. Reduce the number of data points acquired to 5,000, thereby both speeding the acquisition time and confining the entire trace to within the running track.

2. Change the upper filter setting as discussed in Appendix III to 2,750 cycles per inch. This value is calculated so as to assure that stylus radius effects are eliminated.

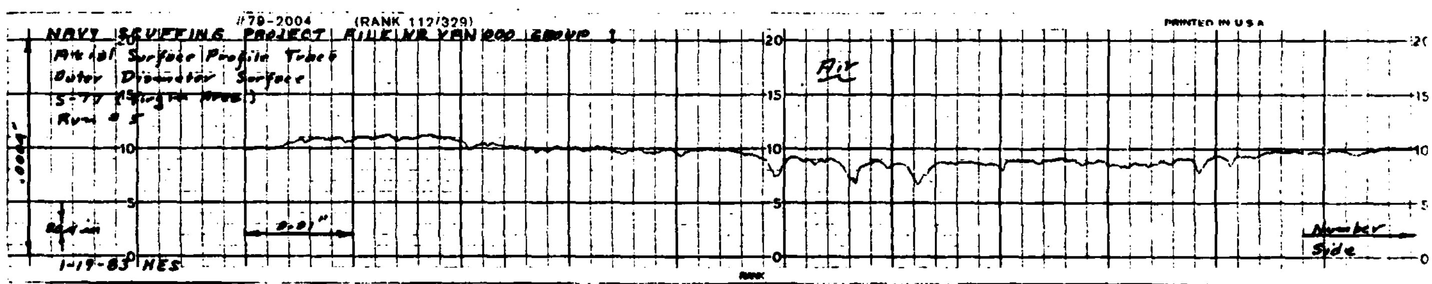
3. Make two traces in the unrun area of both a polished and ground specimen for reference purposes.

7.3 Repeated Tracing-Axial Direction

Figures 13 through 17 show sections of the Talysurf traces obtained in the repeat measurements. Figure 13 shows the traces over the unrun area of polished specimen No. S-77 and ground specimen No. S-81. All of the traces in Figures 13 through 14 were made at magnification of 5,000X and thus are directly comparable. Figure 13 confirms the difference in roughness in the polished and ground specimens and is consistent with the SEM photographs of the unrun sections of these two specimens shown in



GROUND



POLISHED

FIGURE 13: PROFILE TRACES OF UNRUN SURFACES

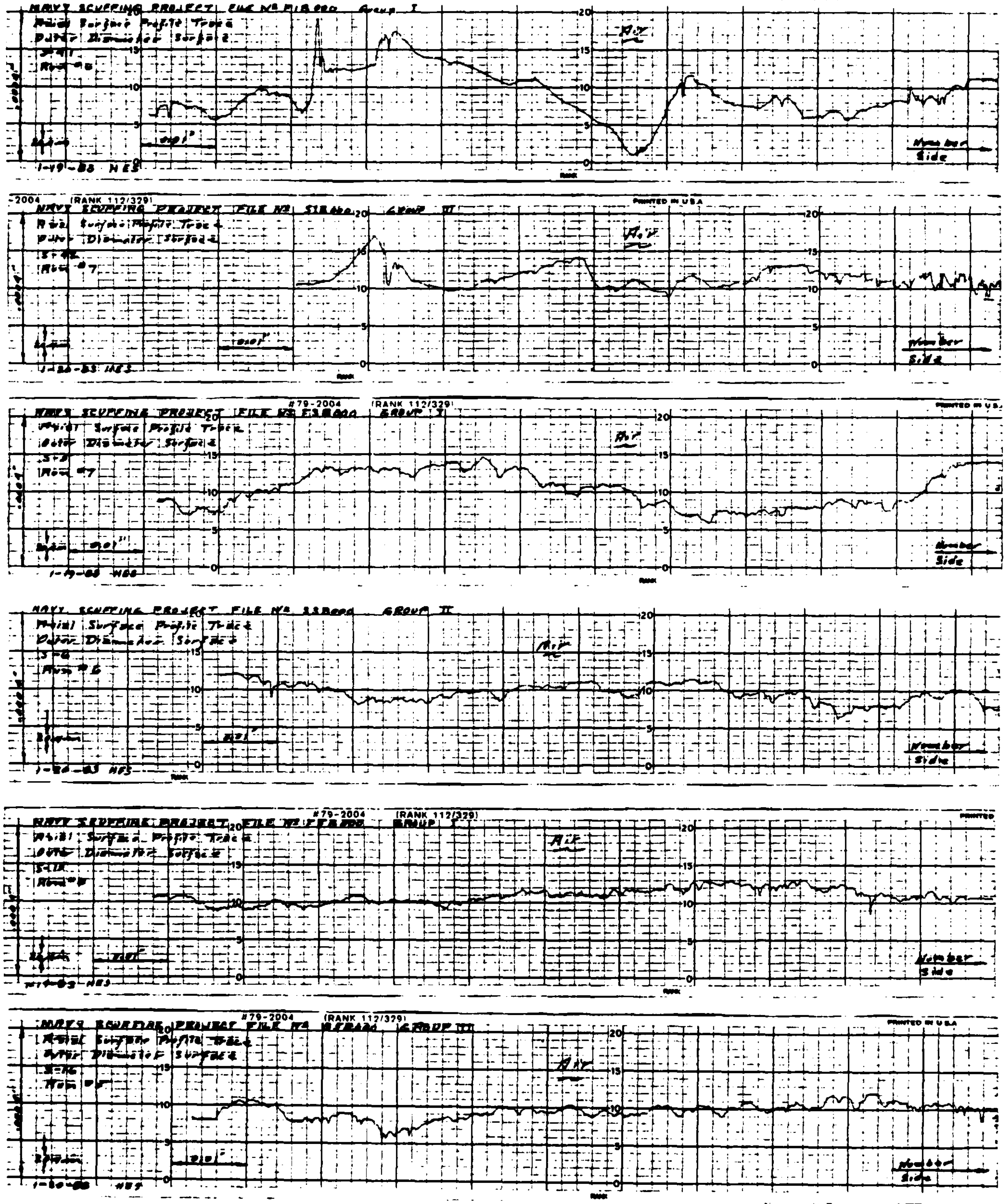


FIGURE 14: PROFILE TRACES OF RUN SURFACES
GROUND - UNSCUFFED

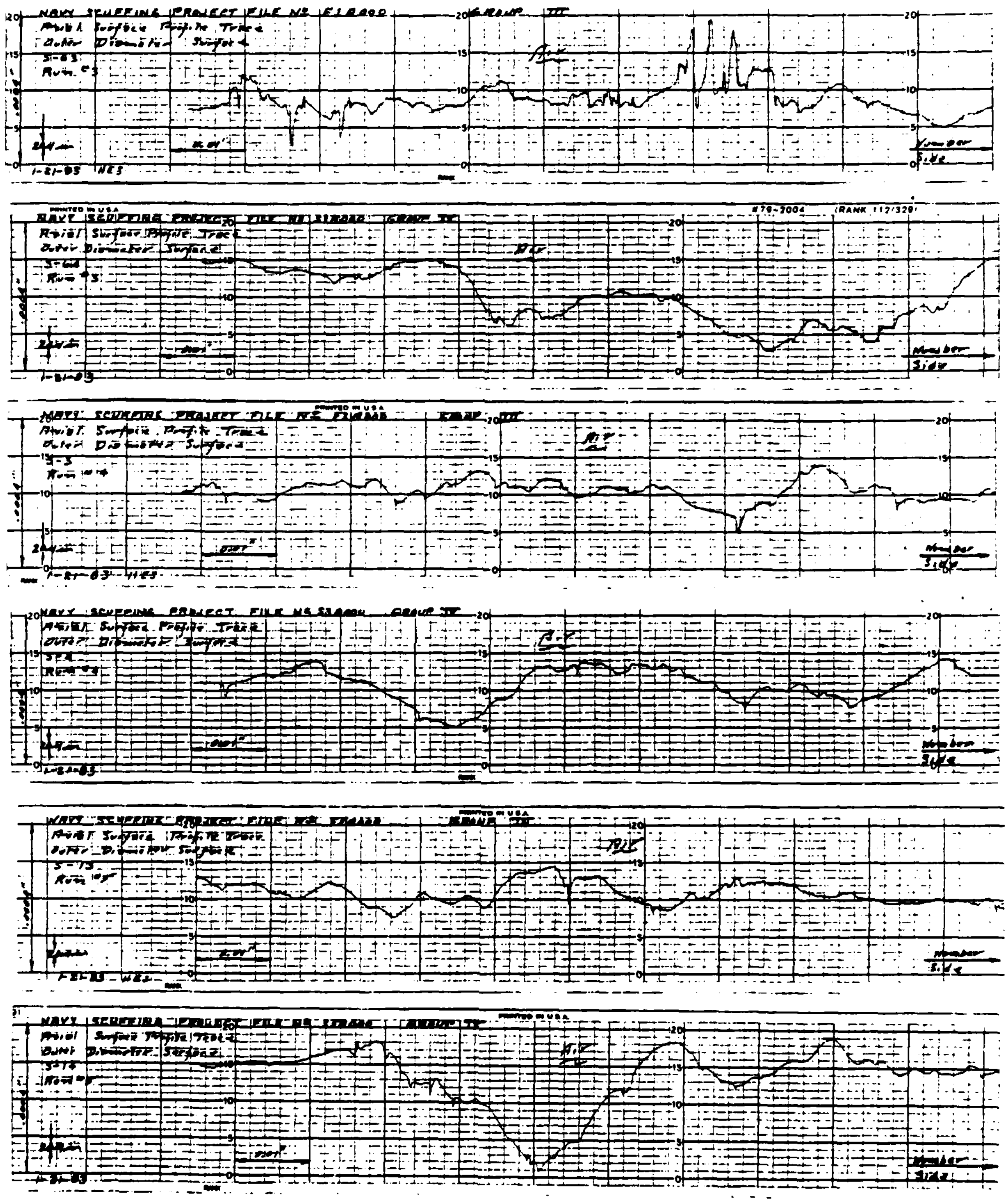


FIGURE 15: PROFILE TRACES OF RUN SURFACES
GROUND - SCUFFED

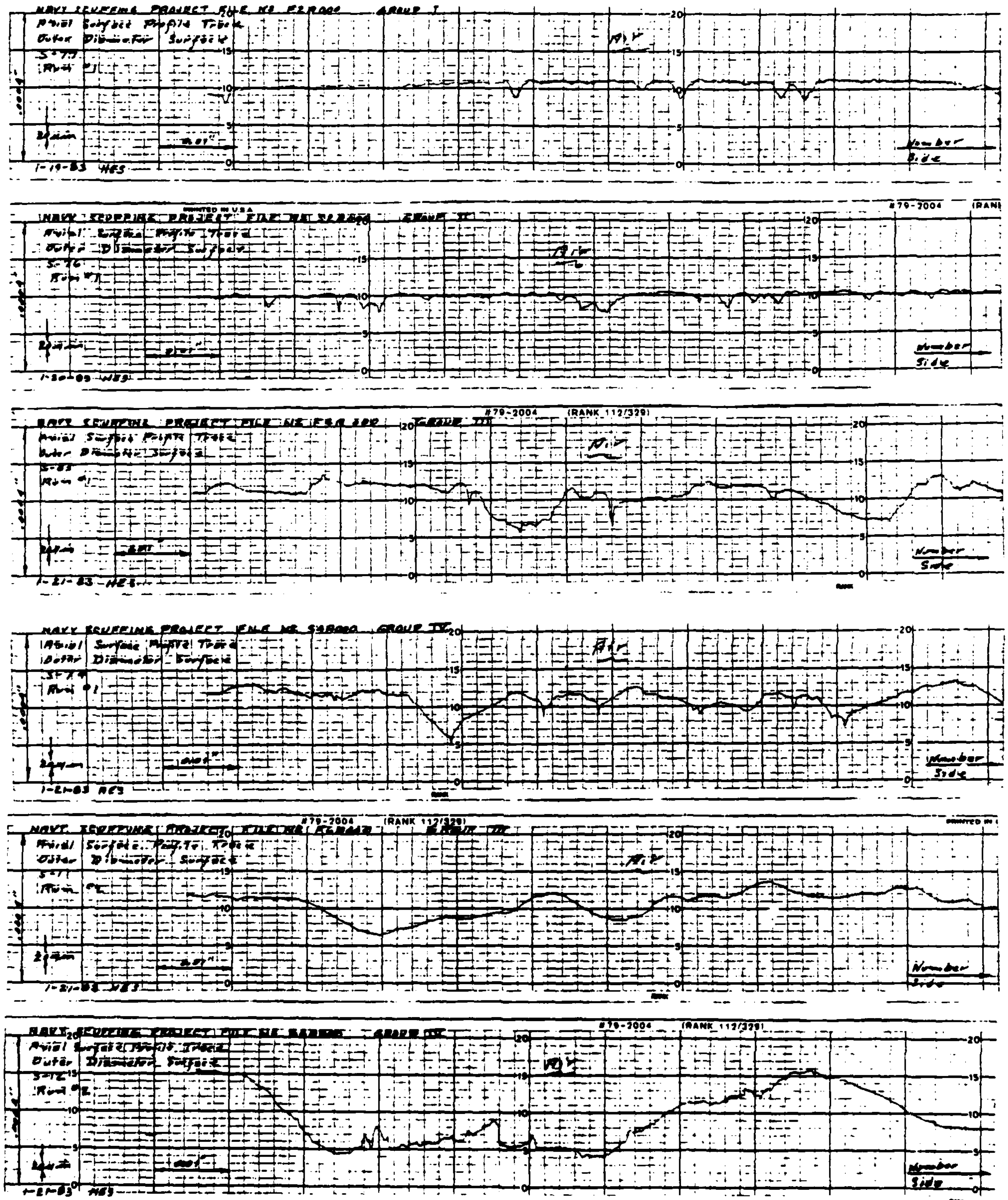


FIGURE 16: PROFILE TRACES OF RUN SURFACES
POLISHED - SCUFFED

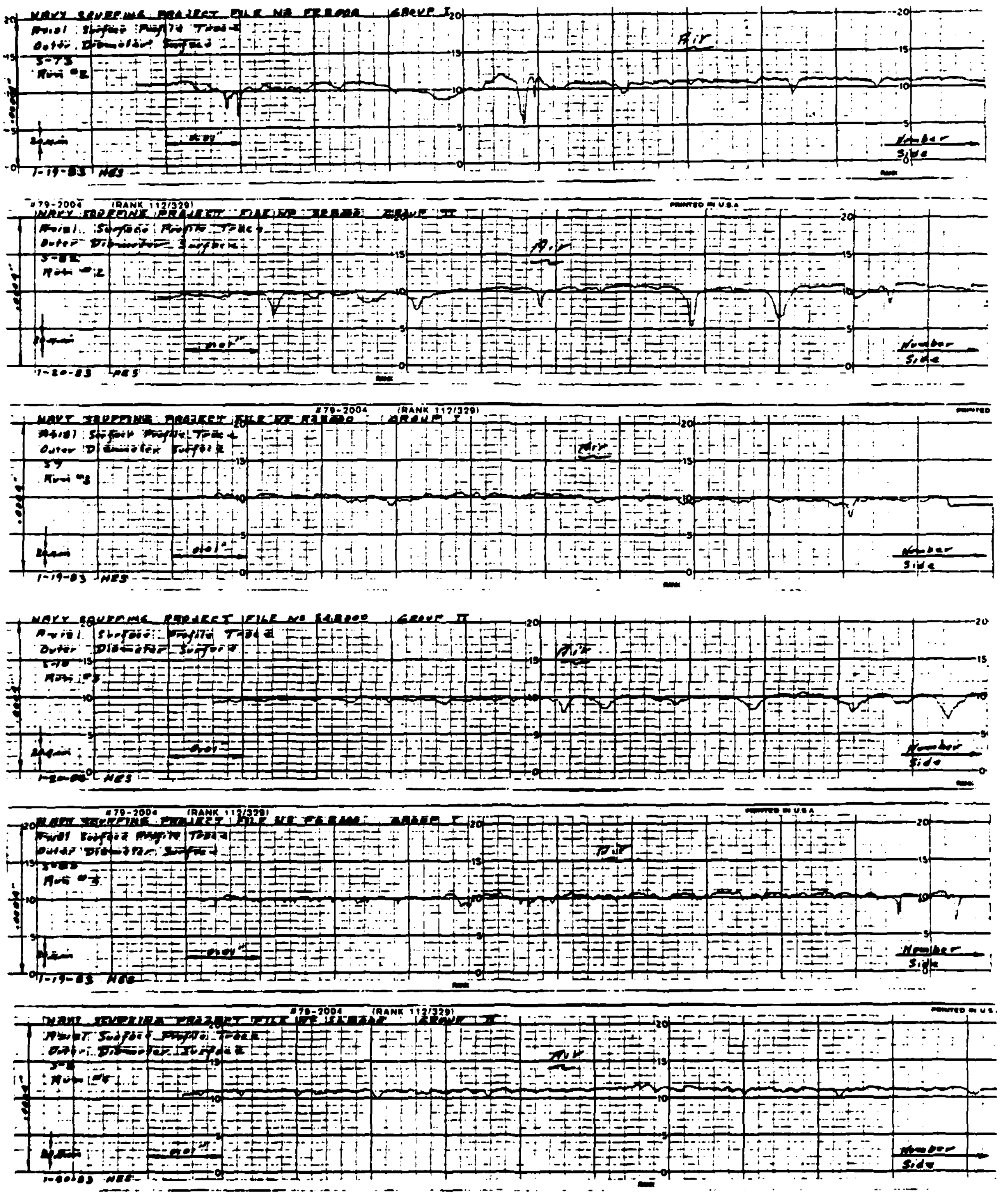


FIGURE 17: PROFILE TRACES OF RUN SURFACES
POLISHED - UNSCUFFED

Figure 7. Figure 14 shows the ground specimens that scuffed; Figure 15 the ground specimens from the tests that were not run to scuffing. Figure 16 shows the polished specimens that scuffed and Figure 17 the polished specimens that did not. Qualitatively, the ground, scuffed specimens seem to be distinguishable from the polished, unscuffed, specimens, but in all, the differences among the four categories are surprisingly small. Within the ground specimens it is difficult to argue that the scuffed and the unscuffed are distinguishable. Within the polished specimens one could argue that the scuffed appear to be rougher than the unscuffed.

Figure 18 shows the histogram produced by PRODOE for an unrun portion of the ground surface of specimen No. S-81. It is reasonably symmetrical, suggestive of a gaussian height distribution. Figure 19 is the histogram of an unrun portion of polished specimen No. S-77. This histogram shows a longer left tail consistent with the fact that polishing tends to remove peaks while leaving valleys undisturbed. Histograms for the four specimen categories, "ground-scuffed", "ground-unscuffed", "polished-scuffed", "polished-unscuffed", are included in Appendices IV through VII for reference.

Table 4 shows the values of m_0, m_2, and m_4 obtained from the single axial profiles with high-pass filtering at 33 cycles/in.

HISTOGRAM OF FILE DK VGN0000FF

MAX = 0.73794E+02 MIN = -0.76627E+02

TOTAL NUMBER OF POINTS = 294.

UPPER CELL BOUNDARY	NORMALIZED CUMULATIVE FREQUENCY	POINT FREQUENCY	
-0.67226E+02	0.0068	2	XX
-0.57824E+02	0.0272	6	XXXXXX
-0.48423E+02	0.0340	2	XX
-0.39022E+02	0.0612	8	XXXXXXXX
-0.29621E+02	0.1429	24	XXXXXXXXXXXXXXXXXXXXXXXX
-0.20219E+02	0.2109	20	XXXXXXXXXXXXXXXXXXXX
-0.10818E+02	0.3299	35	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.14166E+01	0.4660	40	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.79847E+01	0.5884	36	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.17386E+02	0.7517	48	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.26787E+02	0.8537	30	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.36189E+02	0.9184	19	XXXXXXXXXXXXXXXXXXX
0.45590E+02	0.9694	15	XXXXXXXXXXXXXXX
0.54991E+02	0.9898	6	XXXXXX
0.64393E+02	0.9932	1	X
0.73794E+02	1.0000	2	XX

FIGURE 18: HISTOGRAM - UNRUN GROUND SURFACE

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HISTOGRAM OF FILE DK VFN000OFF

MAX = 0.22378E+02 MIN = -0.43733E+02

TOTAL NUMBER OF POINTS = 294.

UPPER CELL BOUNDARY	NORMALIZED CUMULATIVE FREQUENCY	POINT FREQUENCY	
-0.39601E+02	0.0034	1	X
-0.35469E+02	0.0034	0	
-0.31337E+02	0.0068	1	X
-0.27205E+02	0.0170	3	XXX
-0.23073E+02	0.0238	2	XX
-0.18941E+02	0.0408	5	XXXXX
-0.14809E+02	0.0612	6	XXXXXX
-0.10677E+02	0.1156	16	XXXXXXXXXXXXXXXX
-0.65453E+01	0.2381	36	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.24133E+01	0.3878	44	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.17186E+01	0.5612	51	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.58506E+01	0.7075	43	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.99825E+01	0.8333	37	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.14114E+02	0.9320	29	XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.18246E+02	0.9796	14	XXXXXXXXXXXXXX
0.22378E+02	1.0000	6	XXXXXX

FIGURE 19: HISTOGRAM - UNRUN POLISHED SURFACE

F-4185C-1-R100

	SPECIMEN NO./FILE NO.	CALIBRATION CONSTANT (μin/count)	m_0 (μin)^2	m_2	m_4 (μin)$^{-2}$
GROUND-SCUFFED	S-63/F1A	0.1011	1150	9.07E-3	7.61E-7
	S-64/S1A	0.1042	1143	1.26E-3	1.57E-7
	S-3/F3A	0.1011	694	8.64E-4	9.18E-8
	S-4/S3A	0.1042	726	5.59E-4	6.54E-8
	S-13/F5A	0.1011	574	9.61E-4	1.13E-7
	S-14/S5A	0.1042	2185	1.55E-3	1.87E-7
GROUND-UNSCUFFED	S-41/F1B	0.1140	1908	3.68E-3	3.93E-7
	S-42/S1B	0.1030	831	1.59E-3	1.80E-7
	S-5/F3B	0.1140	248	1.48E-3	2.28E-7
	S-6/S3B	0.1030	196	8.23E-4	9.73E-8
	S-15/F5B	0.1140	126	1.22E-3	1.69E-7
	S-16/S5B	0.1030	162	9.68E-4	1.24E-7
POLISHED-SCUFFED	S-77/F2A	0.1140	142	6.86E-4	0.821E-7
	S-76/S2A	0.1030	128	6.73E-4	0.673E-7
	S-85/F4A	0.1011	433	9.05E-4	0.924E-7
	S-74/S4A	0.1042	701	1.09E-3	1.27 E-7
	S-11/F6A	0.1011	342	2.47E-4	0.335E-7
	S-12/S6A	0.1042	536	1.40E-3	1.78 E-7
POLISHED-UNSCUFFED	S-73/F2B	0.1140	295	2.68E-3	2.69 E-7
	S-81/S2B	0.1030	255	1.03E-3	0.633E-7
	S-9/F4B	0.1140	53	6.90E-4	1.01 E-7
	S-10/S4B	0.1030	97	5.50E-4	0.723E-7
	S-83/F6B	0.1140	53	1.42E-3	2.27 E-7
	S-8/S6B	0.1030	25	3.78E-4	0.427E-7
GROUND - UNRUN	S-81/VGN	0.1140	668	1.15E-2	1.79 E-6
POLISHED - UNRUN	S-80/VPN	0.1140	103	6.30E-4	7.75 E-8

TABLE 4: SPECTRAL MOMENTS FROM SINGLE AXIAL TRACE AFTER FILTERING - UPPER FILTER SETTING = 2750 CYCLES/IN.

and low-pass filtering at 2,750 cycles/in. The values are grouped into four categories: "ground-scuffed", "ground-unscuffed", "polished-scuffed", and "polished-unscuffed". There is substantial variability in m_0, m_2, and m_4 within each of the four categories. Also shown are the corresponding values for the unrun ground and polished surfaces.

7.4 Variability

Church [13,21] has derived theoretical expressions for the coefficient of variation (standard deviation divided by the mean) of spectral moments corresponding to spectra of the form

$$s(f) \sim f^{-n}$$

for various n. Sayles & Thomas [14] have compiled numerous examples showing the universality of the "inverse square" spectrum corresponding to the special case of the above spectrum having n = 2. For this case Church's expression for the coefficient of variation of m_0 is

$$\gamma_0 = (1/\sqrt{3})\ (\sqrt{D/L})$$

where D is the period of the lowest frequency present in the data and L is the record length. With ΔX = 14.5E-6 in. and N = 5,000 points, the record length L is

$$L = N\Delta X = 5{,}000 \bullet 14.5E{-}6 = 0.07236 \text{ in.}$$

By filtering at a lower cutoff frequency of f = 33 cpi, the value of the lowest frequency present is D = 1/33 = 0.0303 in. Thus, the coefficient of variation of m_0 is predicted to be

$$\gamma_0 = 1/\sqrt{3}\ \sqrt{0.0303/0.07236} = 0.374$$

The observed coefficient of variation of m_0 in each of the four categories shown on Table 4 are:

Ground-Scuffed	Ground-Unscuffed	Polished-Scuffed	Polished-Unscuffed
0.550	1.21	0.590	0.885

The fact that the observed values are higher than theoretical suggests that there are real differences among the specimens in each category, i.e. the spread is larger than expected due to chance alone. Nonetheless, the statistical variability is quite high, because D is large relative to L.

8.0 DATA ANALYSIS

The values of m_0, m_2 and m_4 from Table 4 are repeated in Table 5. These values were used as input to program ASPERSIM to compute the micro-contact conditions corresponding to the contact of the slow and fast disks of each test. The disk surfaces were regarded as isotropic and separated by a distance equal to the calculated plateau film thickness calculated at the conjunction temperature. Based on the spectral moments m_0, m_2 a m_4 from a single trace on an isotropic surface the 9 bispectral moments needed for ASPERSIM input are:

$$m_{02} = m_{20} = m_2$$

$$m_{11} = m_{13} = m_{31} = 0$$

$$m_{22} = m_4/3$$

$$m_{04} = m_{40} = m_4$$

$$m_{00} = m_0$$

Table 5 lists for the four specimen categories the ASPERSIM output:

ZNCON: Contacts per in^2

TOTF: Elastically supported load per unit

AVF: The area average force supported by individual asperity contacts

	SPEC. NO.	TEST NO.	P (lbs)	T_c-°F CONJ. TEMP.	σ (μin)	m_0 (μin^2)	m_2	m_4 (μin^{-2}) $x10^{-7}$	h/σ	a (in)	b (in)	NO. OF CONTACTS n	ZNCON CONTACTS PER in^2	TOTF CONTRACT LOAD/UNIT AREA (lbs/in^2)	AVF ASPERITY LOAD (lbs)	TOTA CONTACT AREA/ UNIT AREA	AVA AVERAGE ASPERITY CONTACT AREA
GROUND - SCUFFED	S-63	F1A	966	457	47.9	1150	9.07E-3	7.61	0.082	9.15E-2	2.13E-2	1.127E4	1.84E6	4.17E5	0.227	0.223	1.21E-7
	S-64	S1A	966	457	47.9	1143	1.26E-3	1.57	0.082	9.15E-2	2.13E-2	1.127E4	1.84E6	4.17E5	0.227	0.223	1.21E-7
	S-3	F3A	3516	415	37.7	694	8.64E-4	.918	0.099	14.1 E-2	3.28E-2	2.702E4	1.86E6	3.93E5	0.211	0.392	2.10E-7
	S-4	S3A	3516	415	37.7	726	5.59E-4	.654	0.099	14.1 E-2	3.28E-2	2.702E4	1.86E6	3.93E5	0.211	0.392	2.10E-7
	S-13	F5A	1466	367	52.5	574	9.61E-4	1.13	0.141	10.5 E-2	2.44E-2	1.553E4	1.93E6	5.59E5	0.289	0.403	2.08E-7
	S-14	S5A	1466	367	52.5	2185	1.55E-3	1.87	0.141	10.5 E-2	2.44E-2	1.553E4	1.93E6	5.59E5	0.289	0.403	2.08E-7
GROUND - UNSCUFFED	S-41	F1B	483	341	52.3	1908	3.68E-3	3.93	0.112	7.26E-2	1.69E-2	7.401E3	1.92E6	4.99E5	0.260	0.299	1.56E-7
	S-42	S1B	483	341	52.3	831	1.59E-3	1.80	0.112	7.26E-2	1.69E-2	7.401E3	1.92E6	4.99E5	0.260	0.299	1.56E-7
	S-5	F3B	1758	392	21.1	248	1.48E-3	2.28	0.201	11.2 E-2	2.60E-2	2.388E4	2.61E6	2.02E5	0.077	0.217	8.29E-8
	S-6	S3B	1758	392	21.1	196	8.23E-4	.973	0.201	11.2 E-2	2.60E-2	2.388E4	2.61E6	2.02E5	0.077	0.217	8.29E-8
	S-15	F5B	718	306	17.0	126	1.22E-3	1.69	0.588	8.33E-2	1.94E-2	1.000E4	1.97E6	9.14E4	0.046	0.116	5.92E-8
	S-16	S5B	718	306	17.0	162	9.68E-4	1.24	0.588	8.33E-2	1.94E-2	1.000E4	1.97E6	9.14E4	0.046	0.116	5.92E-8
POLISHED - SCUFFED	S-77	F2A	1166	425	16.4	142	6.86E-4	.821	0.260	9.74E-2	2.27E-2	1.403E4	2.02E6	1.29E5	0.064	0.189	9.37E-8
	S-76	S2A	1166	425	16.4	128	6.73E-4	.673	0.260	9.74E-2	2.27E-2	1.403E4	2.02E6	1.29E5	0.064	0.189	9.37E-8
	S-85	F4A	3716	425	33.7	433	9.05E-4	.924	0.226	14.4 E-2	3.34E-2	2.659E4	1.76E6	2.79E5	0.158	0.271	1.54E-7
	S-74	S4A	3716	425	33.7	701	1.09E-3	1.27	0.226	14.4 E-2	3.34E-2	2.659E4	1.76E6	2.79E5	0.158	0.271	1.54E-7
	S-11	F6A	2116	491	29.6	342	2.47E-4	.335	0.177	11.9 E-2	2.76E-2	2.218E4	2.15E6	2.92E5	0.136	0.302	1.41E-7
	S-12	S6A	2116	491	29.6	536	1.40E-3	1.78	0.177	11.9 E-2	2.76E-2	2.218E4	2.15E6	2.92E5	0.136	0.302	1.41E-7
POLISHED - UNSCUFFED	S-73	F2B	583	312	23.4	295	2.68E-3	2.69	0.276	7.73E-2	1.80E-2	7.868E3	1.80E6	1.71E5	0.095	0.167	9.28E-8
	S-81	S2B	583	312	23.4	255	1.03E-3	.633	0.276	7.73E-2	1.80E-2	7.868E3	1.80E6	1.71E5	0.095	0.167	9.28E-8
	S-9	F4B	1858	350	12.2	53	6.90E-4	1.01	0.398	11.4 E-2	2.65E-2	2.325E4	2.45E6	8.99E4	0.037	0.149	6.10E-8
	S-10	S4B	1858	350	12.2	97	5.50E-4	.723	0.398	11.4 E-2	2.65E-2	2.325E4	2.45E6	8.99E4	0.037	0.149	6.10E-8
	S-83	F6B	1058	326	8.83	53	1.42E-3	2.27	1.01	9.44E-2	2.19E-2	1.344E4	2.07E6	3.09E4	0.015	0.056	2.71E-8
	S-8	S6B	1058	326	8.83	25	3.78E-4	.427	1.01	9.44E-2	2.19E-2	1.344E4	2.07E6	3.09E4	0.015	0.056	2.71E-8

TABLE 5: SPECTRAL MOMENTS AND ASPERSIM OUTPUT

AT83D013

TOTA: The elastic contact area per unit nominal area i.e. the ratio of real to apparent contact area

AVA: The area of an average asperity contact

The loads and areas computed by ASPERSIM are based on the assumption that the micro-contacts deform elastically. Even though with thin films, most if not all, asperities will undergo plastic deformation, the ASPERSIM output is descriptive of the severity of surface conditions, reflecting as it does the conditions that prevail prior to the onset of plastic flow.

Also listed in Table 5 are the load at scuffing or test termination, calculated conjunction temperature, the standard deviation of the composite surface of the two mating disks $\sigma = [(m_0)fast + (m_0)slow]^{1/2}$, the contact ellipse major and minor axes a and b based on the scuffing load for the scuffed specimens or on the load at test termination for the unscuffed specimens, and n, the expected number of asperity contacts over the macro-contact ellipse computed as the product of ZNCON and the area of the contact ellipse πab.

8.1 Conjunction Temperature

Figure 20 is a plot of scuffing load against conjunction temperature. The plot illustrates that the conjunction temperature is not constant at scuffing for either ground or polished specimens, nor is there a clear relationship between scuffing load and conjunction temperature.

8.2 Film Parameter

Figure 21 is a plot of scuffing load against film parameter h/σ. For constant test conditions one might expect scuffing load to either increase with or at least not decrease with film parameter. This plot shows that the other factors, i.e. sliding speed, rolling speed and finish type are sufficiently influential to mask any film parameter effect which might exist.

8.3 Correlation of Scuffing Load With ASPERSIM Parameters

For the tests that proceeded to scuffing it is seen from the data in Table 5 that both n and AVA increase monotonically with scuffing load. AVF also increases monotonically with scuffing load for the polished specimen tests but fails to do so for the ground specimen tests. The fact that n increases with scuffing load is almost unavoidable since the contact area increases with load and ZNCON does not vary appreciably. Figure 22 is a plot of

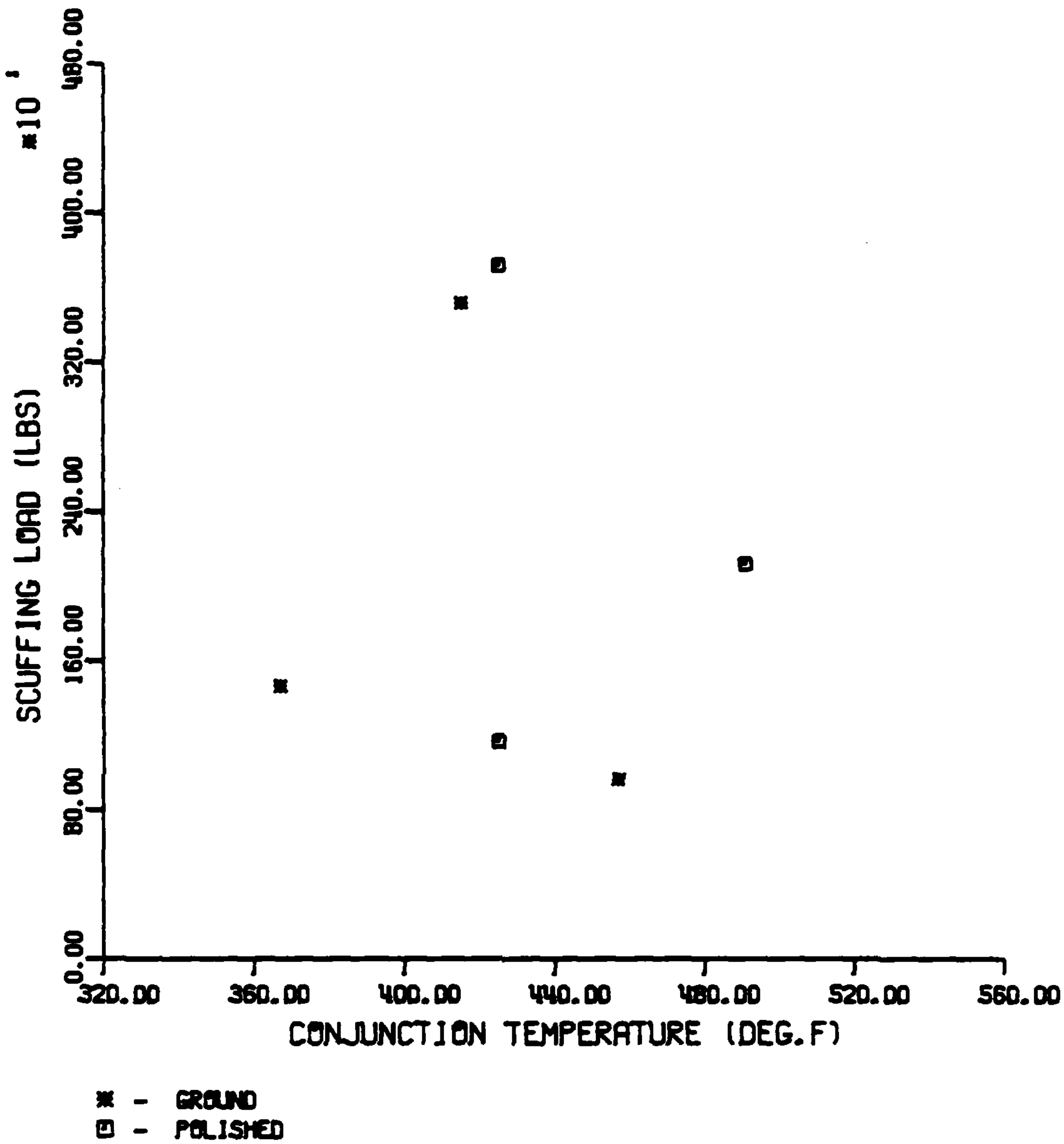

FIGURE 20: SCUFFING LOAD
VS.
CONJUNCTION TEMPERATURE

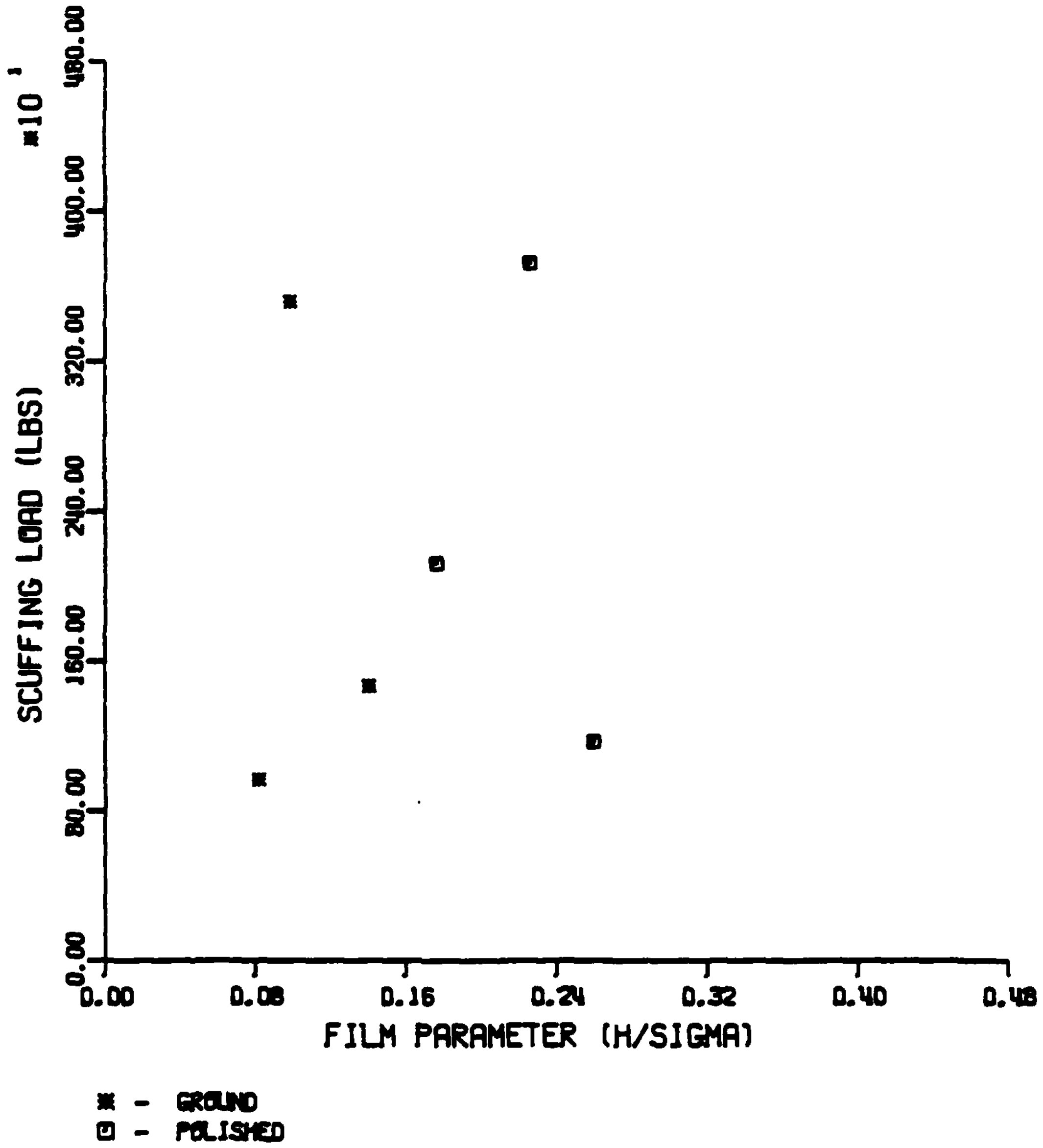

FIGURE 21: SCUFFING LOAD VS. FILM PARAMETER

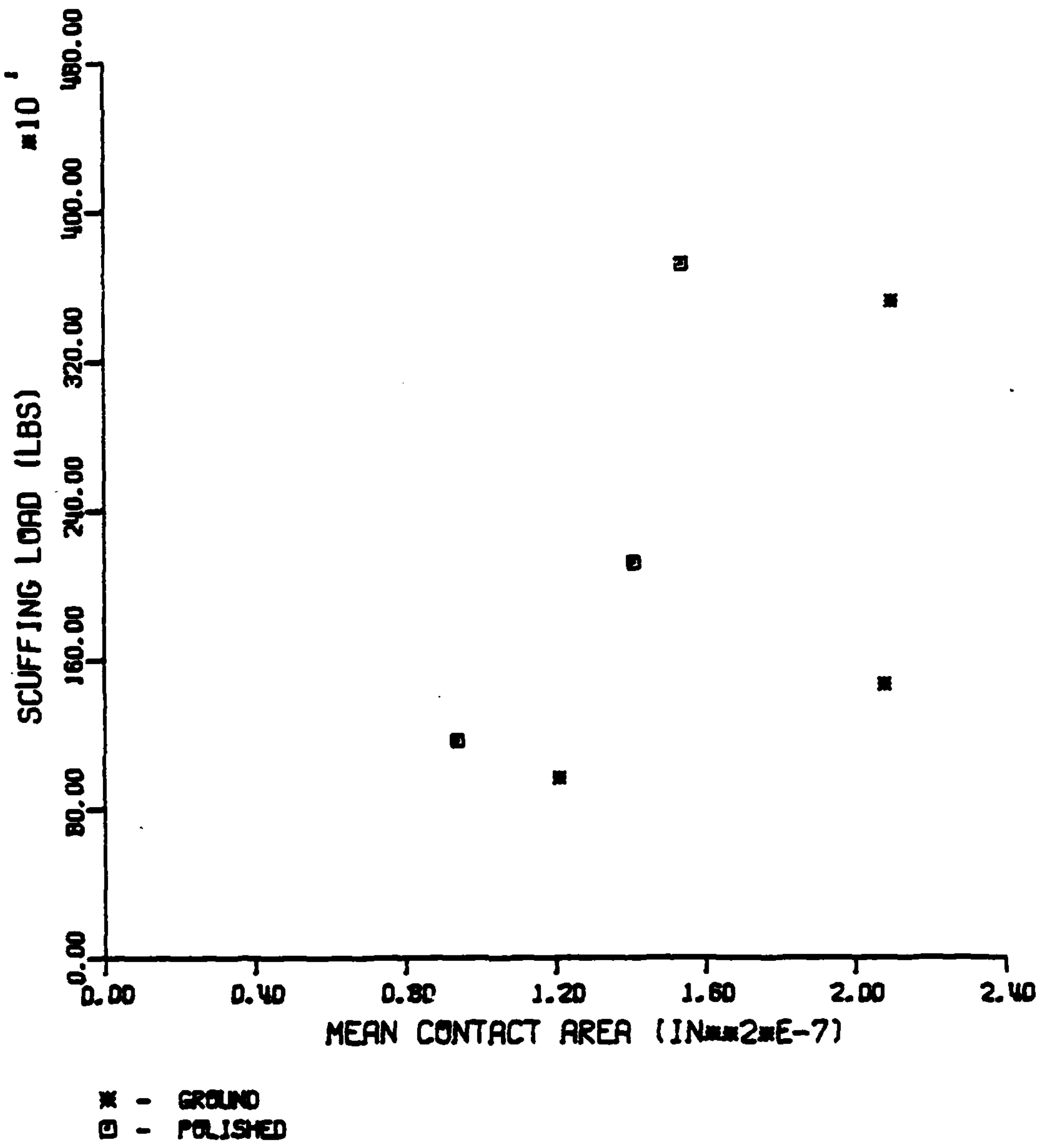

FIGURE 22: SCUFFING LOAD VS. MEAN AREA OF CONTACT

scuffing load against AVA. The fact that scuffing load increases with AVA does not necessarily imply that large AVA values serve to increase the load at which scuffing occurs. More likely it reflects the evolutionary change in microgeometry with load. This is supported by the fact that for each kinematic condition AVA and AVF are higher for the ground specimens than for the polished specimens even though the scuffing load is always lower for the ground specimens. Run-in is discussed further in Section 8.5 below.

8.4 Comparison of Polished vs. Ground and Scuffed vs. Unscuffed Results

Table 6 summarizes by finish type and scuffing status the average values of m_0, m_2 and m_4, the ASPERSIM output values, AVA, AVF and ZNCON, and the conjunction temperature Tc and the film parameter h/σ.

Program No. BMDP2V of the Biomedical System of Computer Programs for Statistical Analysis,[1] was used to evaluate the statistical significance of the observed differences in m_0, m_2 and

[1]Winer [5] has, however, proposed a flash temperature correction factor of $[1-0.7\sigma]^{-1}$ (σ = CLA roughness in μm).

	GROUND - SCUFFED	GROUND - UNSCUFFED	POLISHED - SCUFFED	POLISHED - UNSCUFFED
m_0 $(\mu in)^2$	1080	579	380.	130
m_2 (10^{-3})	2.38	1.63	0.834	1.12
m_4 $(\mu in)^{-2}(10^{-7})$	2.29	1.99	0.967	1.29
AVF (lbs)	.215	.111	.097	.035
AVA (in^2)	1.64	.866	1.10	0.460
N	15.5E3	9.97E3	16.0E3	7.16E3
T_c (°F)	377	319	407	305
h/σ	0.315	.668	.595	1.27

TABLE 6: MEAN VALUES BY FINISH TYPE AND SCUFFING STATUS

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m_4 between finish type and scuffing condition. In performing this analysis the 6 specimens at each combination of finish type (F) and scuffing condition (S) were treated as independent replicate tests. Actually since these six specimens were run at three different speed combinations they are not true replicates. The scatter among these tests is thus higher than it would be among pure replicates and the differences found to be significant by treating the data in this way are sure to be significant if pure replicates were used.

The analysis of variance tables are listed in Table 7. Effects for which the value listed under "Tail Probability" is less than 0.010 are statistically significant at the 10% level. With this criterion it is seen that m_0 differs significantly between the two finishes and between the scuffed and unscuffed specimens. The interaction is negligible however, meaning that the effect of finish is comparable for the scuffed and unscuffed specimens. m_2 and m_4 do not differ with respect to finish type or scuffing status at a 10% level of significance, but the m_4 effect is nearly significant between finish type.

Program BMDP2V was also applied to evaluate the significance of the observed differences between AVA, AVF and N. Since these quantities are determined by a pair of disks, there are only 3

F-418SC-1-R100

ANALYSIS OF VARIANCE FOR 1-ST DEPENDENT VARIABLE - M0

	SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F	TAIL PROBABILITY
	MEAN	14089421.00000	1	14089821.00000	21.62	0.002
	F	3947961.00000	1	3947961.00000	6.06	0.039
	S	1691246.00000	1	1691246.00000	2.60	0.146
	FS	186748.00000	1	186748.00000	0.29	0.607
1	ERROR	5213555.00000	8	651694.77500		

ANALYSIS OF VARIANCE FOR 1-ST DEPENDENT VARIABLE - M2

	SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F	TAIL PROBABILITY
	MEAN	106.70137	1	106.70137	15.00	0.005
	F	12.53162	1	12.53162	1.76	0.221
	S	0.63617	1	0.63617	0.09	0.772
	FS	3.24791	1	3.24791	0.46	0.518
1	ERROR	56.88879	8	7.11110		

ANALYSIS OF VARIANCE FOR 1-ST DEPENDENT VARIABLE - M4

	SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F	TAIL PROBABILITY
	MEAN	128.13783	1	128.13783	26.29	0.001
	F	12.21486	1	12.21486	2.51	0.152
	S	0.00105	1	0.00105	0.00	0.989
	FS	1.19890	1	1.19890	0.25	0.633
1	ERROR	38.99060	8	4.87383		

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TABLE 7: ANALYSIS OF VARIANCE SUMMARY - m_0, m_2 AND m_4

observations for each combination of finish type and scuffing status. The analysis of variance summaries are given in Table 8. AVA and AVF both differ significantly with finish type and scuffing status, with ground specimens having larger average area and larger force.

The contact density is the same for scuffed specimens irrespective of original finish type. The scuffed specimens tend to have a lower contact density than the unscuffed specimens though the difference is not statistically significant.

Finally, BMDP2V was applied to the conjunction temperature values (Tc) and the film parameter values (HSIG). The respective analysis of variance summaries are given in Table 9. It is seen that Tc varies significantly with scuffing status but not at all with finish type. Of course, conjunction temperature must be higher for the scuffed specimens because flash temperature is a function of load and the unscuffed tests only reached half the load of the corresponding unscuffed tests.

For the film parameter there is a significant effect of scuffing status and an indication of an effect of finish. On balance, AVA and AVF are more sensitive than film parameter and, unlike conjunction temperature, indicate a finish effect.

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ANALYSIS OF VARIANCE FOR 1-ST DEPENDENT VARIABLE - AVA

	SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F	TAIL PROBABILITY
	MEAN	16.48999	1	16.48999	91.42	0.000
	F	0.59630	1	0.59630	3.31	0.107
	S	1.67776	1	1.67776	9.30	0.016
	FS	0.00913	1	0.00913	0.05	0.829
1	ERROR	1.44296	8	0.18037		

ANALYSIS OF VARIANCE FOR 1-ST DEPENDENT VARIABLE - AVF

	SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F	TAIL PROBABILITY
	MEAN	0.21735	1	0.21735	45.29	0.000
	F	0.03050	1	0.03050	6.36	0.036
	S	0.02567	1	0.02567	5.35	0.049
	FS	0.00147	1	0.00147	0.31	0.595
1	ERROR	0.03839	8	0.00480		

ANALYSIS OF VARIANCE FOR 1-ST DEPENDENT VARIABLE - ZNCON

	SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F	TAIL PROBABILITY
	MEAN	49.53183	1	49.53183	668.53	0.000
	F	0.00120	1	0.00120	0.02	0.902
	S	0.13230	1	0.13230	1.79	0.218
	FS	0.01920	1	0.01920	0.26	0.624
1	ERROR	0.59267	8	0.07408		

TABLE 8: ANALYSIS OF VARIANCE SUMMARY - AVERAGE ASPERITY AREA (AVA), AVERAGE ASPERITY FORCE (AVF), AND AVERAGE DENSITY OF CONTACTS (ZNCON)

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ANALYSIS OF VARIANCE FOR 1-ST DEPENDENT VARIABLE - TC

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F	TAIL PROBABILITY
MEAN	1768700.00000	1	1768700.00000	1236.92	0.000
F	216.74609	1	216.74609	0.15	0.707
S	25483.99219	1	25483.99219	17.82	0.003
FS	1950.74609	1	1950.74609	1.36	0.276
1 ERROR	11439.39063	8	1429.92383		

ANALYSIS OF VARIANCE FOR 1-ST DEPENDENT VARIABLE - HSIG

SOURCE	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	F	TAIL PROBABILITY
MEAN	1.06207	1	1.06207	19.19	0.002
F	0.10528	1	0.10528	1.90	0.205
S	0.21333	1	0.21333	3.85	0.085
FS	0.01628	1	0.01628	0.29	0.602
1 ERROR	0.44281	8	0.05535		

TABLE 9: ANALYSIS OF VARIANCE SUMMARY - CONJUNCTION TEMPERATURE (TC) AND FILM PARAMETER (HSIG)

8.5 Run-In

Run-in effects were not specifically studied in this investigation i.e. roughness characterizations were not made of the same surfaces at various stages of running. Nevertheless comparable surfaces on different specimens were characterized in the unrun condition, at the time of scuffing and at a half the time to scuffing.

Using the measured microgeometry of the unrun surfaces in Table 4, the surface velocities common to Tests 1A and 2A and the oil temperature (180°F) at start up, it was possible to compute the ASPERSIM variables for two ground and two polished disc specimens at start up conditions. The resultant values along with the values at the same velocities and at the conjunction temperature at half scuffing (Tests 1B and 2B) at scuffing (Tests 1A and 2A), are listed in Table 10.

In the same manner the microgeometry at half scuffing and at scuffing for tests 1A, 2A, 1B and 2B) was used with the 180°F start up oil temperature to calculate the comparable ASPERSIM characteristics of surfaces run-in to this extent. These values are shown in Table 10.

The parameter AVF is sma. er for the polished than the ground surfaces and although AVF increases with running the difference

	h/σ	ZNCON CONTACTS/ (in^2)	AVF (LBS)	AVA (in^2)	
GROUND	.367	3.23E6	.099	4.33E-8	(UNRUN)
POLISHED	.919	1.23E6	.033	5.77E-8	
GROUND	.268	1.75E6	.240	14.6E-8	(HALF SCUFFING)
POLISHED	.590	1.40E6	.075	7.82E-8	
GROUND	.280	1.66E6	.203	11.1E-8	(AT SCUFFING)
POLISHED	.805	1.23E6	.044	7.14E-8	

TABLE 10: SURFACE PARAMETERS AT START UP CONDITIONS FOR THREE LEVELS OF RUN-IN

V_S = 138 IN/SEC

V_R = 345 IN/SEC

between finishes persists. AVA on the other hand is initially smaller for the ground than the polished surfaces. For the run-in surfaces the polished specimens have a lower AVA value.

The contact density ZNCON, like AVF is also higher in each case for the ground than for the polished specimens at, each stage of run-in. This suggests the use of the product ZNCON x AVF, as a further candidate inverse measured of scuffing proneness. This parameter has the physical meaning of asperity supported force per unit area.

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APPENDIX I

SIGNAL PROCESSING FOR SURFACE ROUGHNESS PARAMETERS

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SIGNAL PROCESSING FOR SURFACE ROUGHNESS PARAMETERS

Surface Roughness Characterization

The roughness or microscale topography of contacting bodies is generally recognized as a main determinant of their friction and wear behavior. The most commonly used measure of roughness of precision manufactured parts is the mean absolute deviation of the heights of a profile trace from their mean. This quantity, also known as the centerline average (CLA) or arithmetic average (AA) is the roughness measure adopted by the American National Standards Institute in Standard ANSI B46.1 on Surface Texture [16].

Other measures, dependent on the height distribution of profiles are in more limited use. One such is the root mean square (RMS) profile height; others are the skewness and kurtosis. RMS and CLA both measure essentially the same thing; scatter about the mean. For a given amplitude distribution function they are related to each other by a multiplicative constant e.g. for a gaussian amplitude height distribution function, RMS = 1.25 • CLA. Skewness and kurtosis measure the asymmetry and peakedness of the distribution of profile heights and serve generally to detect departures of the height distribution function from the gaussian shape.

Two surfaces could differ drastically in the distance between, and in the sharpness of, the surface summits and still have the same CLA, RMS, skewness and kurtosis. Yet is is the density of summits and summit curvature as well as summit height that determines the severity and extent of the interaction that takes place when microscopically rough surfaces roll or slide on each other.

Moreover although surface <u>summits</u> determine the surface's performance the most commonly used equipment for surface roughness analysis is based upon stylus <u>profile</u> traces. Peaks on profiles generally represent the shoulders of asperities, i.e. the mean peak height will be lower than the mean summmit height. In addition, apparent frequencies on anisotropic surfaces will vary with the direction of tracing.

In [17] Nayak proposed a comprehensive system for characterizing general anisotropic surfaces as two dimensional random processes. Effectively this system overcame all of the shortcomings of using just the CLA. This work specialized to solid surfaces the findings of Longuet-Higgins [18] for ocean waves.

Two Dimensional Spectral Density

The point of departure in the two dimensional random process description is the notion of a two dimensional spectrum, whereby the total variability of the surface is decomposed into contributions from spatial frequencies measured in two orthogonal directions.

Let ω_x and ω_y represent the radian frequency of the surface in the two orthogonal directions "x" and "y". The spectral density $S(\omega_x, \omega_y)$ has the property that the variability (variance) due to surface waves having frequencies between ω_x and $\omega_x+\Delta\omega_x$ in the "x" direction and between ω_y and $\omega_y+\Delta\omega_y$ in the "y" direction is given for $\Delta\omega_y$ and $\Delta\omega_x$ small, by

$$\mathrm{var}[\omega_x, \omega_y] = S(\omega_x,\omega_y)\ \Delta\omega_x\ \Delta\omega_y \qquad \text{(I-1)}$$

The two dimensional spectral moment m_{ij} is defined as

$$m_{ij} = \iint \omega_x{}^i\ \omega_y{}^j\ S(\omega_x,\omega_y)\ d\omega_x\ d\omega_y \qquad \text{(I-2)}$$

Nayak showed that for a microhertzian model in which surface summits are approximated as elliptical paraboloids, the surface may be described by the even order two dimensional spectral moments of all orders up to four. This constitutes nine numbers: m_{00}, m_{02}, m_{11}, m_{20}, m_{04}, m_{13}, m_{22}, m_{31} and m_{40}.

These nine values appear as parameters in the joint distribution of summit height and principal curvature and in the expressions for summit density.

Estimating Two Dimensional Spectral Moments

The link between profile traces and surface summit statistics is established by the relationship that these statistics have to the one dimensional spectral moments measured along a profile trace taken at an angle θ from the x direction.

Denoting frequencies measured in this direction by ω_θ and the associated (one dimensional) spectral density $S(\omega_\theta)$ then the even spectral moments of order 0, 2 and 4 are:

$$m_0(\theta) = \int \omega_\theta{}^0 \, S(\omega_\theta) \, d\omega_\theta \qquad \text{(I-3)}$$

$$m_2(\theta) = \int \omega_\theta{}^2 \, S(\omega_\theta) \, d\omega_\theta \qquad \text{(I-4)}$$

$$m_4(\theta) = \int \omega_\theta{}^4 \, S(\omega_\theta) \, d\omega_\theta \qquad \text{(I-5)}$$

These values can be estimated in two ways, namely by either (1) estimating the spectral density and using numerical integration to approximate Eqs. (I-3) to (I-5) or (2) by using the relations:

$$m_0 = E(z-\mu)^2 \tag{I-6}$$

$$m_2 = E(dz/dx)^2 \tag{I-7}$$

$$m_4 = E[(dz^2/dx^2)^2] \tag{I-8}$$

where z(x) denotes a profile made in direction x and μ is the mean line of the profile.

For digital processing given n profile height values $z_1 \ldots z_n$ equispaced a distance Δx apart, the quantities m_0, m_2 and m_4 may be computed as:

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$$m_0 = \sum_{i=1}^{n} (z_{i-\mu})^2/n \tag{I-9}$$

$$m_2 = \sum_{i=1}^{n-1} (z_{i+1} - z_i)^2/(n-1)(\Delta x)^2 \tag{I-10}$$

$$m_4 = \sum_{i=2}^{n-2} (z_{i+1} - 2z_i + z_{i-1})^2/(\Delta x)^4(n-2) \tag{I-11}$$

Given the values of m_0, m_2 and m_4 for traces made at different angles θ_1, $\theta_2 \ldots\ldots \theta_k$ on the surface with respect to an arbitrary coordinate system coincident with the surface mean plane, the bispectral moments can be fit by using multiple regression with the following theoretical relationships [cf. McCool [8]]

$$m_0(\theta_i) = m_{00} \qquad \text{(I-12)}$$

$$m_2(\theta_i) = m_{20}\cos^2\theta_i + 2m_{11}\cos\theta_i\sin\theta_i + m_{02}\sin^2\theta_i \qquad \text{(I-13)}$$

$$m_4(\theta_i) = m_{40}\cos^4\theta_i + 4m_{31}\cos^3\theta_i\sin\theta_i + 6m_{22}\cos^2\theta_i\sin^2\theta_i$$

$$+ 4m_{13}\cos\theta_i\sin^2\theta_i + m_{04}\sin^4\theta_i \qquad \text{(I-14)}$$

APPENDIX II

UPPER LIMIT ON m_4 IMPOSED BY STYLUS RADIUS

APPENDIX II

UPPER LIMIT ON m_4 IMPOSED BY STYLUS RADIUS

Church [19] has pointed out that the mean square curvature in stylus traces is limited by the stylus radius R.

A stylus of radius R cannot detect sharper curvatures than its own radius. Thus the measured curvature must exceed 1/R.

Let z(x) denote the equation of a profile. Since dz/dx is small, dz^2/dx^2 is approximately the curvature at any value of x and at the peaks where dz/dx = 0, it is exactly the curvature. Thus

$$1/d^2z/dx^2 > R \qquad \text{(II-1)}$$

or $$d^2z/dx^2 < 1/R \qquad \text{(II-2)}$$

and $$(d^2z/dx^2)^2 < R^{-2} \qquad \text{(II-3)}$$

Since m_4 is the average value of $(d^2z/dx^2)^2$ (cf. Appendix) then one must have

$$m_4 < R^{-2} \qquad \text{(II-4)}$$

For R = 10^{-4} = 10^2 μ in. the standard stylus radius used with the Talysurf IV, an upper limit on m_4 is

$$m_4 < (10^2)^{-2} = 10^{-4} \quad (\mu\text{in})^{-2}$$

APPENDIX III

UPPER FREQUENCY DETERMINATION FOR BANDPASS FILTERING

APPENDIX III

UPPER FREQUENCY DETERMINATION FOR BANDPASS FILTERING

A well known result [cf.20] is that a stylus of radius R will be able to touch the valleys of a sinusoidal surface of amplitude B so long as the frequency f does not exceed

$$f = 1/2\pi \ (RB)^{-1/2} \qquad \text{(III-1)}$$

The mean square height of a sinewave, m_0, is

$$m_0 = B^2/2 \qquad \text{(III-2)}$$

Therefore a random surface having mean square height m_0 will have the same mean square height as an equivalent sinewave having amplitude

$$B = (2m_0)^{1/2} \qquad \text{(III-3)}$$

The upper frequency for traceability of the equivalent sinewave is then, from Eq.(III-1)

$$f = 1/2\pi \ \left(R(2m_0)^{1/2} \right)^{-1/2} \qquad \text{(III-4)}$$

For $R = 10^{-4}$ in. this becomes

$f = 13.38\ (m_0)^{-1/4}$

Using $m_0 = 575\ (\mu in)^2$ for ground and $m_0 = 90\ (\mu in)^2$ for polished specimens gives, after rounding to the nearest 50 cycles/in.

$$f = 2{,}750 \text{ (ground)}$$

$$= 4{,}350 \text{ (polished)}$$

It is quite likely that good information can be obtained without stylus distortion at frequencies higher than given by this calculation since the actual random surface will not have all of its energy *concentrated* at a *single frequency* as assumed in this calculation. It is therefore quite justifiable to assert that the signal is not affected by stylus distortion at frequencies below the limit calculated as above.

Inasmuch as the value of the upper cutoff has a strong effect on the number of contacts, the value 2750 has been used in processing both ground and polished specimen roughness data to assure comparability.

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APPENDIX IV

HISTOGRAMS

GROUND-SCUFFED SPECIMENS

F-0185C-1-R100

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HISTOGRAM OF FILE DK S5A000OFF

MAX =  0.81662E+02  MIN = -0.11528E+03

TOTAL NUMBER OF POINTS =      294.

 UPPER CELL    NORMALIZED  POINT
 BOUNDARY      CUMULATIVE  FREQUENCY
               FREQUENCY
-0.10297E+03    0.0170        5  XXXXX
-0.90661E+02    0.0374        6  XXXXXX
-0.78352E+02    0.0646        8  XXXXXXXX
-0.66043E+02    0.1088       13  XXXXXXXXXXXXX
-0.53734E+02    0.1395        9  XXXXXXXXX
-0.41425E+02    0.1939       16  XXXXXXXXXXXXXXXX
-0.29117E+02    0.2755       24  XXXXXXXXXXXXXXXXXXXXXXXX
-0.16808E+02    0.3639       26  XXXXXXXXXXXXXXXXXXXXXXXXXX
-0.44991E+01    0.4864       36  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.78096E+01    0.5850       29  XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.20118E+02    0.6599       22  XXXXXXXXXXXXXXXXXXXXXX
 0.32427E+02    0.7211       18  XXXXXXXXXXXXXXXXXX
 0.44736E+02    0.7959       22  XXXXXXXXXXXXXXXXXXXXXX
 0.57045E+02    0.8639       20  XXXXXXXXXXXXXXXXXXXX
 0.69354E+02    0.9320       20  XXXXXXXXXXXXXXXXXXXX
 0.81662E+02    1.0000       20  XXXXXXXXXXXXXXXXXXXX
```

HISTOGRAM OF FILE DK F5A0000FF

MAX = 0.60037E+02 MIN = -0.10868E+03

TOTAL NUMBER OF POINTS = 294.

UPPER CELL BOUNDARY	NORMALIZED CUMULATIVE FREQUENCY	POINT FREQUENCY	
-0.98137E+02	0.0034	1	X
-0.87593E+02	0.0034	0	
-0.77048E+02	0.0034	0	
-0.66503E+02	0.0034	0	
-0.55958E+02	0.0136	3	XXX
-0.45413E+02	0.0170	1	X
-0.34868E+02	0.0306	4	XXXX
-0.24323E+02	0.1463	34	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.13778E+02	0.3231	52	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.32327E+01	0.5408	64	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.73123E+01	0.6667	37	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.17857E+02	0.7653	29	XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.28402E+02	0.8571	27	XXXXXXXXXXXXXXXXXXXXXXXXXXX
0.38947E+02	0.9490	27	XXXXXXXXXXXXXXXXXXXXXXXXXXX
0.49492E+02	0.9796	9	XXXXXXXXX
0.60037E+02	1.0000	6	XXXXXX

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```
HISTOGRAM OF FILE DK S3A0000FF

MAX =  0.59196E+02  MIN = -0.63131E+02

TOTAL NUMBER OF POINTS =      294.

 UPPER CELL   NORMALIZED  POINT
 BOUNDARY     CUMULATIVE  FREQUENCY
              FREQUENCY
-0.55485E+02   0.0000         0
-0.47840E+02   0.0306         9  XXXXXXXXX
-0.40194E+02   0.0884        17  XXXXXXXXXXXXXXXXX
-0.32549E+02   0.1565        20  XXXXXXXXXXXXXXXXXXXX
-0.24903E+02   0.1871         9  XXXXXXXXX
-0.17258E+02   0.2347        14  XXXXXXXXXXXXXX
-0.96127E+01   0.3469        33  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.19672E+01   0.4456        29  XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.56782E+01   0.5884        42  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.13324E+02   0.6905        30  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.20969E+02   0.7721        24  XXXXXXXXXXXXXXXXXXXXXXXX
 0.28614E+02   0.8537        24  XXXXXXXXXXXXXXXXXXXXXXXX
 0.36260E+02   0.8946        12  XXXXXXXXXXXX
 0.43905E+02   0.9184         7  XXXXXXX
 0.51551E+02   0.9728        16  XXXXXXXXXXXXXXXX
 0.59196E+02   1.0000         8  XXXXXXXX
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AD-A146 544 EFFECT OF ASPERITY INTERACTIONS ON SCUFFING(U) SKF TECHNOLOGY SERVICES KING OF PRUSSIA PA J I MC COOL MAY 84 SKF-AT83D013 NAPC-PE-94-C N00140-80-C-1538 2/2

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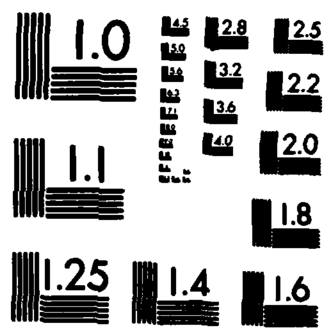

OPY RESOLUTION TEST CHART

F-4185C-1-R100

HISTOGRAM OF FILE DK F3A0000FF

MAX = 0.64526E+02 MIN = -0.79962E+02

TOTAL NUMBER OF POINTS = 294.

UPPER CELL BOUNDARY	NORMALIZED CUMULATIVE FREQUENCY	POINT FREQUENCY	
-0.70932E+02	0.0102	3	XXX
-0.61901E+02	0.0238	4	XXXX
-0.52871E+02	0.0408	5	XXXXX
-0.43840E+02	0.0646	7	XXXXXXX
-0.34810E+02	0.1054	12	XXXXXXXXXXXX
-0.25779E+02	0.1803	22	XXXXXXXXXXXXXXXXXXXXXX
-0.16749E+02	0.2585	23	XXXXXXXXXXXXXXXXXXXXXXX
-0.77182E+01	0.3571	29	XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.13123E+01	0.5306	51	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.10343E+02	0.6837	45	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.19373E+02	0.7925	32	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.28404E+02	0.8605	20	XXXXXXXXXXXXXXXXXXXX
0.37434E+02	0.9252	19	XXXXXXXXXXXXXXXXXXX
0.46465E+02	0.9932	20	XXXXXXXXXXXXXXXXXXXX
0.55495E+02	0.9966	1	X
0.64526E+02	1.0000	1	X

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HISTOGRAM OF FILE DK S1A000OFF

MAX = 0.87638E+02 MIN = -0.60219E+02

TOTAL NUMBER OF POINTS = 294.

UPPER CELL BOUNDARY	NORMALIZED CUMULATIVE FREQUENCY	POINT FREQUENCY	
-0.50978E+02	0.0204	6	XXXXXX
-0.41737E+02	0.0510	9	XXXXXXXXX
-0.32496E+02	0.1701	35	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.23255E+02	0.2925	36	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.14014E+02	0.4320	41	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.47727E+01	0.5510	35	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.44684E+01	0.6259	22	XXXXXXXXXXXXXXXXXXXXXX
0.13710E+02	0.6667	12	XXXXXXXXXXXX
0.22951E+02	0.7347	20	XXXXXXXXXXXXXXXXXXXX
0.32192E+02	0.7823	14	XXXXXXXXXXXXXX
0.41433E+02	0.8163	10	XXXXXXXXXX
0.50674E+02	0.8844	20	XXXXXXXXXXXXXXXXXXXX
0.59915E+02	0.9422	17	XXXXXXXXXXXXXXXXX
0.69156E+02	0.9728	9	XXXXXXXXX
0.78397E+02	0.9966	7	XXXXXXX
0.87638E+02	1.0000	1	X

AT83D013

F-4185C-1-R100

HISTOGRAM OF FILE DK F1A0000FF

MAX = 0.10997E+03 MIN = -0.12306E+03

TOTAL NUMBER OF POINTS =   294.

UPPER CELL BOUNDARY	NORMALIZED CUMULATIVE FREQUENCY	POINT FREQUENCY	
-0.10850E+03	0.0068	2	XX
-0.93934E+02	0.0102	1	X
-0.79369E+02	0.0238	4	XXXX
-0.64804E+02	0.0510	8	XXXXXXXX
-0.50239E+02	0.0782	8	XXXXXXXX
-0.35675E+02	0.0986	6	XXXXXX
-0.21110E+02	0.1939	28	XXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.65448E+01	0.4082	63	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.80200E+01	0.6054	58	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.22585E+02	0.7585	45	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.37150E+02	0.9014	42	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.51715E+02	0.9388	11	XXXXXXXXXXX
0.66279E+02	0.9728	10	XXXXXXXXXX
0.80844E+02	0.9864	4	XXXX
0.95409E+02	1.0000	4	XXXX
0.10997E+03	1.0000	0	

APPENDIX V

HISTOGRAMS

GROUND-UNSCUFFED SPECIMENS

```
HISTOGRAM OF FILE DK F1B000OFF


MAX =  0.20644E+03  MIN = -0.93465E+02


TOTAL NUMBER OF POINTS =      294.

 UPPER CELL   NORMALIZED  POINT
 BOUNDARY     CUMULATIVE  FREQUENCY
              FREQUENCY
-0.74721E+02  0.0510       15  XXXXXXXXXXXXXXX
-0.55976E+02  0.1054       16  XXXXXXXXXXXXXXXX
-0.37232E+02  0.1565       15  XXXXXXXXXXXXXXX
-0.18488E+02  0.2755       35  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.25584E+00  0.5884       92  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.19000E+02  0.7585       50  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.37744E+02  0.8571       29  XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.56488E+02  0.9150       17  XXXXXXXXXXXXXXXXX
 0.75232E+02  0.9354        6  XXXXXX
 0.93976E+02  0.9524        5  XXXXX
 0.11272E+03  0.9898       11  XXXXXXXXXXX
 0.13146E+03  0.9898        0
 0.15021E+03  0.9932        1  X
 0.16895E+03  0.9932        0
 0.18770E+03  0.9966        1  X
 0.20644E+03  1.0000        1  X
```

F-4185C-1-R100

HISTOGRAM OF FILE DK S1B0000FF

MAX = 0.46875E+02 MIN = -0.12562E+03

TOTAL NUMBER OF POINTS = 294.

UPPER CELL BOUNDARY	NORMALIZED CUMULATIVE FREQUENCY	POINT FREQUENCY	
-0.11484E+03	0.0034	1	X
-0.10406E+03	0.0034	0	
-0.93280E+02	0.0068	1	X
-0.82498E+02	0.0068	0	
-0.71717E+02	0.0170	3	XXX
-0.60936E+02	0.0374	6	XXXXXX
-0.50155E+02	0.0612	7	XXXXXXX
-0.39374E+02	0.1088	14	XXXXXXXXXXXXXX
-0.28593E+02	0.1667	17	XXXXXXXXXXXXXXXXX
-0.17812E+02	0.2381	21	XXXXXXXXXXXXXXXXXXXXX
-0.70307E+01	0.3435	31	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.37504E+01	0.5238	53	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.14531E+02	0.6905	49	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.25313E+02	0.8095	35	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.36094E+02	0.9082	29	XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.46875E+02	1.0000	27	XXXXXXXXXXXXXXXXXXXXXXXXXXX

AT83D013

HISTOGRAM OF FILE DK F3B0000FF

MAX = 0.49605E+02 MIN = -0.38587E+02

TOTAL NUMBER OF POINTS = 294.

UPPER CELL BOUNDARY	NORMALIZED CUMULATIVE FREQUENCY	POINT FREQUENCY	
-0.33075E+02	0.0034	1	X
-0.27563E+02	0.0238	6	XXXXXX
-0.22051E+02	0.0748	15	XXXXXXXXXXXXXXX
-0.16539E+02	0.1599	25	XXXXXXXXXXXXXXXXXXXXXXXXX
-0.11027E+02	0.2483	26	XXXXXXXXXXXXXXXXXXXXXXXXXX
-0.55152E+01	0.3741	37	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.32043E-02	0.5000	37	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.55088E+01	0.5986.	29	XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.11021E+02	0.7415	42	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.16533E+02	0.8435	30	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.22045E+02	0.9082	19	XXXXXXXXXXXXXXXXXXX
0.27557E+02	0.9422	10	XXXXXXXXXX
0.33069E+02	0.9898	14	XXXXXXXXXXXXXX
0.38581E+02	0.9932	1	X
0.44093E+02	0.9966	1	X
0.49605E+02	1.0000	1	X

HISTOGRAM OF FILE DK S3B0000FF

MAX = 0.38894E+02 MIN = -0.34250E+02

TOTAL NUMBER OF POINTS = 294.

UPPER CELL BOUNDARY	NORMALIZED CUMULATIVE FREQUENCY	POINT FREQUENCY	
-0.29678E+02	0.0068	2	XX
-0.25107E+02	0.0238	5	XXXXX
-0.20535E+02	0.0782	16	XXXXXXXXXXXXXXXX
-0.15964E+02	0.1565	23	XXXXXXXXXXXXXXXXXXXXXXX
-0.11392E+02	0.2177	18	XXXXXXXXXXXXXXXXXX
-0.68209E+01	0.3027	25	XXXXXXXXXXXXXXXXXXXXXXXXX
-0.22495E+01	0.4252	36	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.23220E+01	0.5510	37	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.68935E+01	0.6429	27	XXXXXXXXXXXXXXXXXXXXXXXXXXX
0.11465E+02	0.7585	34	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.16037E+02	0.8741	34	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.20608E+02	0.9422	20	XXXXXXXXXXXXXXXXXXXX
0.25180E+02	0.9626	6	XXXXXX
0.29751E+02	0.9830	6	XXXXXX
0.34323E+02	0.9966	4	XXXX
0.38894E+02	1.0000	1	X

HISTOGRAM OF FILE DK F5B0000FF

MAX = 0.22416E+02 MIN = -0.42420E+02

TOTAL NUMBER OF POINTS = 294.

UPPER CELL BOUNDARY	NORMALIZED CUMULATIVE FREQUENCY	POINT FREQUENCY	
-0.38367E+02	0.0034	1	X
-0.34315E+02	0.0102	2	XX
-0.30263E+02	0.0102	0	
-0.26211E+02	0.0136	1	X
-0.22159E+02	0.0272	4	XXXX
-0.18106E+02	0.0442	5	XXXXX
-0.14054E+02	0.1054	18	XXXXXXXXXXXXXXXXXX
-0.10002E+02	0.2007	28	XXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.59498E+01	0.3469	43	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.18976E+01	0.4388	27	XXXXXXXXXXXXXXXXXXXXXXXXXXX
0.21546E+01	0.5714	39	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.62068E+01	0.6735	30	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.10259E+02	0.7891	34	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.14311E+02	0.8980	32	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.18363E+02	0.9728	22	XXXXXXXXXXXXXXXXXXXXXX
0.22416E+02	1.0000	8	XXXXXXXX

AT83D013

AT83D013

HISTOGRAM OF FILE DK S5B0000FF

MAX = 0.30587E+02 MIN = -0.43324E+02

TOTAL NUMBER OF POINTS = 294.

UPPER CELL BOUNDARY	NORMALIZED CUMULATIVE FREQUENCY	POINT FREQUENCY	
-0.38705E+02	0.0034	1	X
-0.34085E+02	0.0034	0	
-0.29466E+02	0.0136	3	XXX
-0.24846E+02	0.0170	1	X
-0.20227E+02	0.0544	11	XXXXXXXXXXX
-0.15607E+02	0.1122	17	XXXXXXXXXXXXXXXXX
-0.10988E+02	0.2007	26	XXXXXXXXXXXXXXXXXXXXXXXXXX
-0.63684E+01	0.3163	34	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.17489E+01	0.4218	31	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.28706E+01	0.5680	43	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.74900E+01	0.7075	41	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.12109E+02	0.8265	35	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.16729E+02	0.8912	19	XXXXXXXXXXXXXXXXXXX
0.21348E+02	0.9490	17	XXXXXXXXXXXXXXXXX
0.25968E+02	0.9830	10	XXXXXXXXXX
0.30587E+02	1.0000	5	XXXXX

APPENDIX VI

HISTOGRAMS

POLISHED-SCUFFED SPECIMENS

F-4185C-1-R100

```
HISTOGRAM OF FILE DK F2A0000FF

MAX =  0.36973E+02  MIN = -0.44495E+02

TOTAL NUMBER OF POINTS =      294.

 UPPER CELL   NORMALIZED  POINT
 BOUNDARY     CUMULATIVE  FREQUENCY
              FREQUENCY
 0.39403E+02  0.0068         2  XX
-0.34312E+02  0.0170         3  XXX
-0.29220E+02  0.0374         6  XXXXXX
-0.24128E+02  0.0442         2  XX
-0.19036E+02  0.0646         6  XXXXXX
-0.13945E+02  0.0850         6  XXXXXX
-0.88528E+01  0.1224        11  XXXXXXXXXXX
-0.37610E+01  0.2619        41  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.13307E+01  0.5476        84  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.64225E+01  0.7789        68  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.11514E+02  0.8776        29  XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.16606E+02  0.9286        15  XXXXXXXXXXXXXXX
 0.21698E+02  0.9524         7  XXXXXXX
 0.26790E+02  0.9762         7  XXXXXXX
 0.31881E+02  0.9898         4  XXXX
 0.36973E+02  1.0000         3  XXX
```

```
HISTOGRAM OF FILE DK S200000FF

MAX =  0.30469E+02  MIN = -0.43668E+02

TOTAL NUMBER OF POINTS =       294.

 UPPER CELL    NORMALIZED  POINT
 BOUNDARY      CUMULATIVE  FREQUENCY
               FREQUENCY
-0.39035E+02   0.0034         1  X
-0.34401E+02   0.0034         0
-0.29768E+02   0.0102         2  XX
-0.25134E+02   0.0272         5  XXXXX
-0.20500E+02   0.0408         4  XXXX
-0.15867E+02   0.0748        10  XXXXXXXXXX
-0.11233E+02   0.1429        20  XXXXXXXXXXXXXXXXXXXX
-0.65997E+01   0.2177        22  XXXXXXXXXXXXXXXXXXXXXX
-0.19662E+01   0.3810        48  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.26674E+01   0.6327        74  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.73010E+01   0.7891        46  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.11935E+02   0.8741        25  XXXXXXXXXXXXXXXXXXXXXXXXX
 0.16568E+02   0.9116        11  XXXXXXXXXXX
 0.21202E+02   0.9490        11  XXXXXXXXXXX
 0.25835E+02   0.9864        11  XXXXXXXXXXX
 0.30469E+02   1.0000         4  XXXX
```

F-4185C-1-R100

```
HISTOGRAM OF FILE DK F4A0000FF

MAX =  0.74173E+02  MIN = -0.96757E+02

TOTAL NUMBER OF POINTS =     ' 294.

 UPPER CELL   NORMALIZED  POINT
 BOUNDARY     CUMULATIVE  FREQUENCY
              FREQUENCY
-0.86074E+02  0.0034         1  X
-0.75391E+02  0.0034         0
-0.64707E+02  0.0068         1  X
-0.54024E+02  0.0068         0
-0.43341E+02  0.0102         1  X
-0.32658E+02  0.0374         8  XXXX
-0.21975E+02  0.0918        16  XXXXXXXX
-0.11292E+02  0.2313        41  XXXXXXXXXXXXXXXXXXXX
-0.60857E+00  0.6429       121  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.10075E+02  0.8163        51  XXXXXXXXXXXXXXXXXXXXXXXXX
 0.20758E+02  0.8912        22  XXXXXXXXXXX
 0.31441E+02  0.9286        11  XXXXX
 0.42124E+02  0.9524         7  XXX
 0.52807E+02  0.9626         3  X
 0.63490E+02  0.9762         4  XX
 0.74173E+02  1.0000         7  XXX
```

F-4105C-1-R100

HISTOGRAM OF FILE DK S4A0000FF

MAX = 0.75571E+02 MIN = -0.65641E+02

TOTAL NUMBER OF POINTS = 294.

UPPER CELL BOUNDARY	NORMALIZED CUMULATIVE FREQUENCY	POINT FREQUENCY	
-0.56816E+02	0.0034	1	X
-0.47990E+02	0.0102	2	XX
-0.39164E+02	0.0510	12	XXXXXXXXXXXX
-0.30338E+02	0.1190	20	XXXXXXXXXXXXXXXXXXXX
-0.21513E+02	0.2109	27	XXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.12687E+02	0.3367	37	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.38611E+01	0.5068	50	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.49646E+01	0.6054	29	XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.13790E+02	0.6973	27	XXXXXXXXXXXXXXXXXXXXXXXXXXX
0.22616E+02	0.8027	31	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.31442E+02	0.8707	20	XXXXXXXXXXXXXXXXXXXX
0.40268E+02	0.9014	9	XXXXXXXXX
0.49093E+02	0.9354	10	XXXXXXXXXX
0.57919E+02	0.9898	16	XXXXXXXXXXXXXXXX
0.66745E+02	0.9898	0	
0.75571E+02	1.0000	3	XXX

HISTOGRAM OF FILE DK F6A0000FF

MAX = 0.49389E+02 MIN = -0.37654E+02

TOTAL NUMBER OF POINTS =   294.

UPPER CELL BOUNDARY	NORMALIZED CUMULATIVE FREQUENCY	POINT FREQUENCY	
-0.32214E+02	0.0374	11	XXXXXXXXXXX
-0.26773E+02	0.0748	11	XXXXXXXXXXX
-0.21333E+02	0.1190	13	XXXXXXXXXXXXX
-0.15893E+02	0.2007	24	XXXXXXXXXXXXXXXXXXXXXXXX
-0.10453E+02	0.2959	28	XXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.50126E+01	0.4592	48	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.42759E+00	0.5714	33	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.58678E+01	0.7041	39	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.11308E+02	0.7823	23	XXXXXXXXXXXXXXXXXXXXXXX
0.16748E+02	0.8265	13	XXXXXXXXXXXXX
0.22188E+02	0.8639	11	XXXXXXXXXXX
0.27628E+02	0.9116	14	XXXXXXXXXXXXXX
0.33069E+02	0.9558	13	XXXXXXXXXXXXX
0.38509E+02	0.9660	3	XXX
0.43949E+02	0.9762	3	XXX
0.49389E+02	1.0000	7	XXXXXXX

```
HISTOGRAM OF FILE DK S6A0000FF

MAX =  0.70303E+02  MIN = -0.64730E+02

TOTAL NUMBER OF POINTS =      294.

UPPER CELL     NORMALIZED  POINT
BOUNDARY       CUMULATIVE  FREQUENCY
               FREQUENCY
-0.56290E+02   0.0034       1  X
-0.47851E+02   0.0170       4  XXXX
-0.39411E+02   0.0442       8  XXXXXXXX
-0.30972E+02   0.0986      16  XXXXXXXXXXXXXXXX
-0.22532E+02   0.1701      21  XXXXXXXXXXXXXXXXXXXXX
-0.14093E+02   0.3129      42  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.56532E+01   0.4150      30  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.27864E+01   0.5510      40  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.11226E+02   0.7687      64  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.19665E+02   0.8537      25  XXXXXXXXXXXXXXXXXXXXXXXXX
 0.28105E+02   0.8980      13  XXXXXXXXXXXXX
 0.36544E+02   0.9388      12  XXXXXXXXXXXX
 0.44984E+02   0.9626       7  XXXXXXX
 0.53424E+02   0.9728       3  XXX
 0.61863E+02   0.9898       5  XXXXX
 0.70303E+02   1.0000       3  XXX
```

APPENDIX VII

HISTOGRAMS

POLISHED-UNSCUFFED SPECIMENS

F-4185C-1-R100

```
HISTOGRAM OF FILE DK F2R000OFF

MAX =  0.35580E+02  MIN = -0.11786E+03

TOTAL NUMBER OF POINTS =       294.

 UPPER CELL    NORMALIZED  POINT
 BOUNDARY      CUMULATIVE  FREQUENCY
               FREQUENCY
 0.10827E+03   0.0034        1   X
-0.98678E+02   0.0102        2   X
-0.89088E+02   0.0102        0
-0.79498E+02   0.0102        0
-0.69908E+02   0.0102        0
-0.60318E+02   0.0102        0
-0.50729E+02   0.0204        3   X
-0.41139E+02   0.0238        1   X
-0.31549E+02   0.0272        1   X
 0.21959E+02   0.0374        3   X
-0.12369E+02   0.0884       15   XXXXXXX
 0.27794E+01   0.3741       84   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.68104E+01   0.7483      110   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.16400E+02   0.8844       40   XXXXXXXXXXXXXXXXXXXX
 0.25990E+02   0.9388       16   XXXXXXXX
 0.35580E+02   1.0000       18   XYXXXXXXX
```


SKF TECHNOLOGY SERVICES
SKF INDUSTRIES, INC

```
HISTOGRAM OF FILE DK S2R000OFF

MAX =  0.30696E+02  MIN = -0.83453E+02

TOTAL NUMBER OF POINTS =      294.

 UPPER CELL   NORMALIZED  POINT
 BOUNDARY     CUMULATIVE  FREQUENCY
              FREQUENCY
-0.76319E+02  0.0068        2  XX
 0.69184E+02  0.0068        0
-0.62050E+02  0.0136        2  XX
 0.54916E+02  0.0170        1  X
-0.47781E+02  0.0238        2  XX
 0.40647E+02  0.0306        2  XX
-0.33513E+02  0.0476        5  XXXXX
 0.26378E+02  0.0646        5  XXXXX
-0.19244E+02  0.0884        7  XXXXXXX
-0.12110E+02  0.1293       12  XXXXXXXXXXXX
-0.49752E+01  0.2551       37. XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.21591E+01  0.5646       91  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.92934E+01  0.7993       69  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.16428E+02  0.9252       37  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.23562E+02  0.9592       10  XXXXXXXXXX
 0.30696E+02  1.0000       12  XXXXXXXXXXXX
```

AT83D013

```
HISTOGRAM OF FILE DK F4R000UFF

MAX -  0.18843E+02  MIN = -0.40320E+02

TOTAL NUMBER OF POINTS =      294.

 UPPER CELL  NORMALIZED  POINT
 BOUNDARY    CUMULATIVE  FREQUENCY
             FREQUENCY
-0.36623E+02  0.0034       1  X
-0.32925E+02  0.0034       0
-0.29227E+02  0.0068       1  X
-0.25530E+02  0.0068       0
-0.21832E+02  0.0068       0
-0.18134E+02  0.0068       0
-0.14437E+02  0.0374       9  XXXXXXXXX
-0.10739E+02  0.0816      13  XXXXXXXXXXXXX
-0.70412E+01  0.1531      21  XXXXXXXXXXXXXXXXXXXXX
-0.33435E+01  0.3231      50  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.35423E+00  0.5646      71  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.40519E+01  0.7211      46  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.77496E+01  0.8912      50  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.11447E+02  0.9694      23  XXXXXXXXXXXXXXXXXXXXXXX
 0.15145E+02  0.9932       7  XXXXXXX
 0.18843E+02  1.0000       2  XX
```

AT83D013

F-4185C-1-R100

HISTOGRAM OF FILE DK S4B0000FF

MAX = 0.23629E+02 MIN = -0.38842E+02

TOTAL NUMBER OF POINTS = 294.

UPPER CELL BOUNDARY	NORMALIZED CUMULATIVE FREQUENCY	POINT FREQUENCY	
-0.34938E+02	0.0000	0	
-0.31033E+02	0.0068	2	XX
-0.27129E+02	0.0136	2	XX
-0.23224E+02	0.0170	1	X
-0.19320E+02	0.0272	3	XXX
-0.15415E+02	0.0782	15	XXXXXXXXXXXXXXX
-0.11511E+02	0.1088	9	XXXXXXXXX
-0.76066E+01	0.1701	18	XXXXXXXXXXXXXXXXXX
-0.37022E+01	0.3027	39	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.20218E+00	0.4694	49	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.41066E+01	0.6871	64	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.80110E+01	0.8061	35	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0.11915E+02	0.8912	25	XXXXXXXXXXXXXXXXXXXXXXXXX
0.15820E+02	0.9320	12	XXXXXXXXXXXX
0.19724E+02	0.9796	14	XXXXXXXXXXXXXX
0.23629E+02	1.0000	6	XXXXXX

```
HISTOGRAM OF FILE DK S6R000OFF

MAX =   0.90113E+01   MIN = -0.21880E+02

TOTAL NUMBER OF POINTS =        294.

 UPPER CELL     NORMALIZED   POINT
 BOUNDARY       CUMULATIVE   FREQUENCY
                FREQUENCY
-0.19949E+02    0.0034        1  X
-0.18019E+02    0.0034        0
-0.16088E+02    0.0170        4  XXXX
-0.14157E+02    0.0238        2  XX
-0.12226E+02    0.0306        2  XX
-0.10296E+02    0.0408        3  XXX
-0.83650E+01    0.0578        5  XXXXX
-0.64343E+01    0.0884        9  XXXXXXXXX
-0.45036E+01    0.1429       16  XXXXXXXXXXXXXXXX
-0.25729E+01    0.2415       29  XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
-0.64225E+00    0.3810       41  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.12885E+01    0.5714       56  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.32192E+01    0.7517       53  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.51499E+01    0.8776       37  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.70806E+01    0.9524       22  XXXXXXXXXXXXXXXXXXXXXX
 0.90113E+01    1.0000       14  XXXXXXXXXXXXXX
```

F-4105C-1-R100

```
HISTOGRAM OF FILE DK F6R000UFF

MAX =  0.20073E+02  MIN = -0.32644E+02

TOTAL NUMBER OF POINTS =       294.

 UPPER CELL    NORMALIZED  POINT
 BOUNDARY      CUMULATIVE  FREQUENCY
               FREQUENCY
-0.29349E+02  0.0034         1  X
-0.26054E+02  0.0034         0
-0.22760E+02  0.0034         0
-0.19465E+02  0.0068         1  X
-0.16170E+02  0.0340         8  XXXXXXXX
-0.12875E+02  0.0578         7  XXXXXXX
-0.95804E+01  0.1156        17  XXXXXXXXXXXXXXXXX
-0.62856E+01  0.1837        20  XXXXXXXXXXXXXXXXXXXX
-0.29908E+01  0.2959        33  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.30405E+00  0.5034        61  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.35989E+01  0.6599        46  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.68937E+01  0.8435        54  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.10188E+02  0.9524        32  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 0.13483E+02  0.9864        10  XXXXXXXXXX
 0.16778E+02  0.9966         3  XXX
 0.20073E+02  1.0000         1  X
```

APPENDIX VIII

SCUFFING TEST PROCEDURE

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SCUFFING TEST PROCEDURE

1. The tests are conducted on the Geared Roller Test Machine (Figure A-1) at the following conditions:

   a) Lubricant Bulk Temperature 180°F

   b) Load Incremented 25 lbs/5 min.

2. Test Method - Pre-Start

   a) Charge system with specified lubricant.

   b) Install test rollers (odd # on upper shaft and even # on lower shaft) with numbers facing the geared portion of the shaft.

   c) Obtain the required 180°F bulk lubricant temperature.

   d) Calibrate the load indicator as required prior to start.

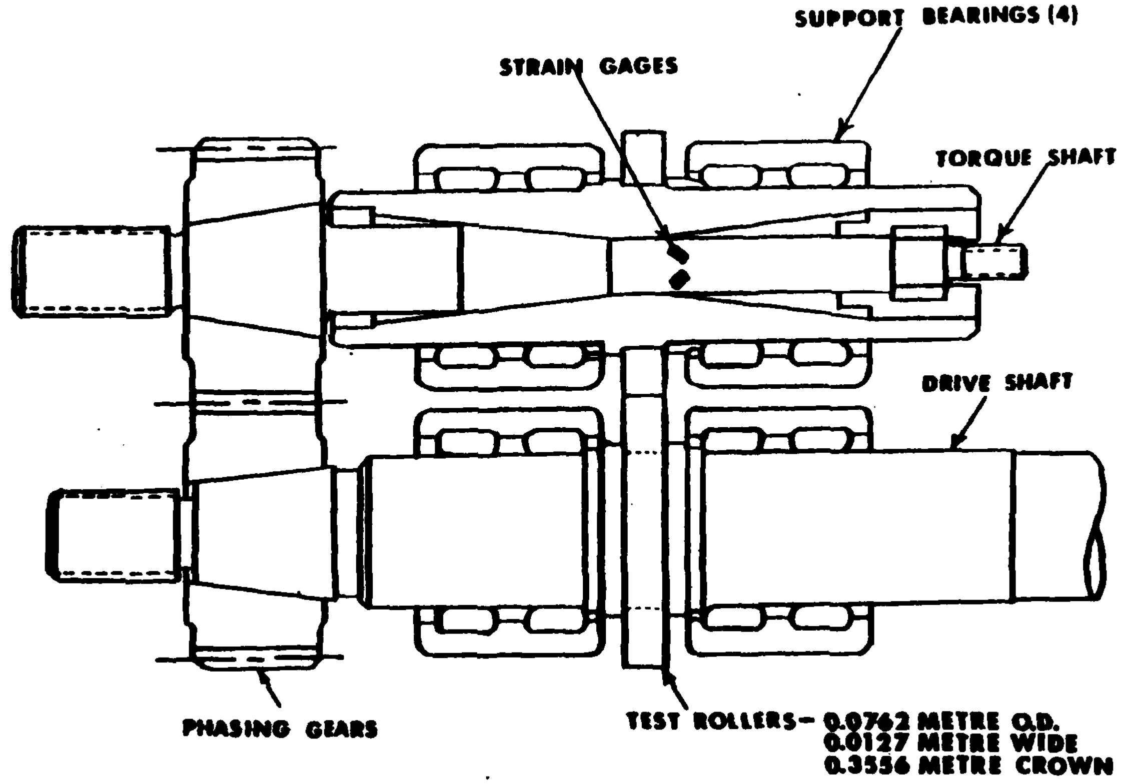
   e) Calibrate Strain Sert to zero.

   f) Check operation of thermocouple on upper and lower rollers.

   g) Apply air pressure as set on gage to 65 lbs maximum.

FIGURE A-1

GEARED ROLLER TEST MACHINE SCHEMATIC



3. Test Method - Procedure AT83D013

a) Reset safety switches to on positions and start system.

b) Start stopwatch and run for 15 minutes at tare load.

c) While at tare load record the following:

(1) Torque at start of load cycle.

(2) Upper and lower roller temperature.

(3) Bulk oil temperature.

(4) Load air pressure.

(5) Pump and inlet oil pressures.

(6) Torgue at end of load cycle.

d) Increase load by 25 lb and record the torque.

e) At the three minute mark record the following:

(1) Upper and lower roller temperature.

(2) Bulk oil temperature.

(3) Load air pressure.

(4) Pump and inlet oil pressures.

(5) Torque at the end of the load cycle.

f) Repeat until a failure is obtained or:

(1) Torque increases by 100 units over the previous load point.

(2) Torque limit of 950 units is reached.

4. Test Method - Unload

a) In some cases it may be necessary to unload the system prior to obtaining a failure. In case of such an event, the following procedure is to be followed:

(1) Reduct load by 50 lb/min and record torque and roller temperature.

(2) On reaching tare load - operate the system for an additional fifteen minutes.

(3) Turn the system off allowing the lubricant to circulate.

5. Test Method - Reload

a) After an unload as described in 5, the following procedure is to be followed to reload the system:

(1) Reach a bulk oil temperature of 180°F.

(2) Calibrate all systems as required.

(3) Turn system on and operate at tare load for fifteen minutes.

(4) Begin load in 100 lb increments every 2 minutes until a 50 lb less than the load at which shutdown occurred.

(5) Begin procedure as outlined in (4). (Note: Record required data at each load point).

6. System Flush - From time to time the operating fluid in the system will be varied. In such an event the following procedure should be followed in order to insure of no contamination.

a) Drain system including all lines.

b) Fill sump with approximately 2 gallons of hexane and start pump and operate 10 minutes.

c) Rinse all parts in hexane.

d) Drain system and add 2 gallons Hercolube A.

e) Start pump - operate for 10 minutes.

f) Drain system and add 1.5 gallons of test fluid and rinse all other parts in test fluid - remove filter element.

g) Operate pump for 10 minutes.

h) Drain system - add new filter element - fill sump with test fluid to level of heater elements.

END

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